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PAPERS IN PRESS FOR FORTHCOMING ISSUES

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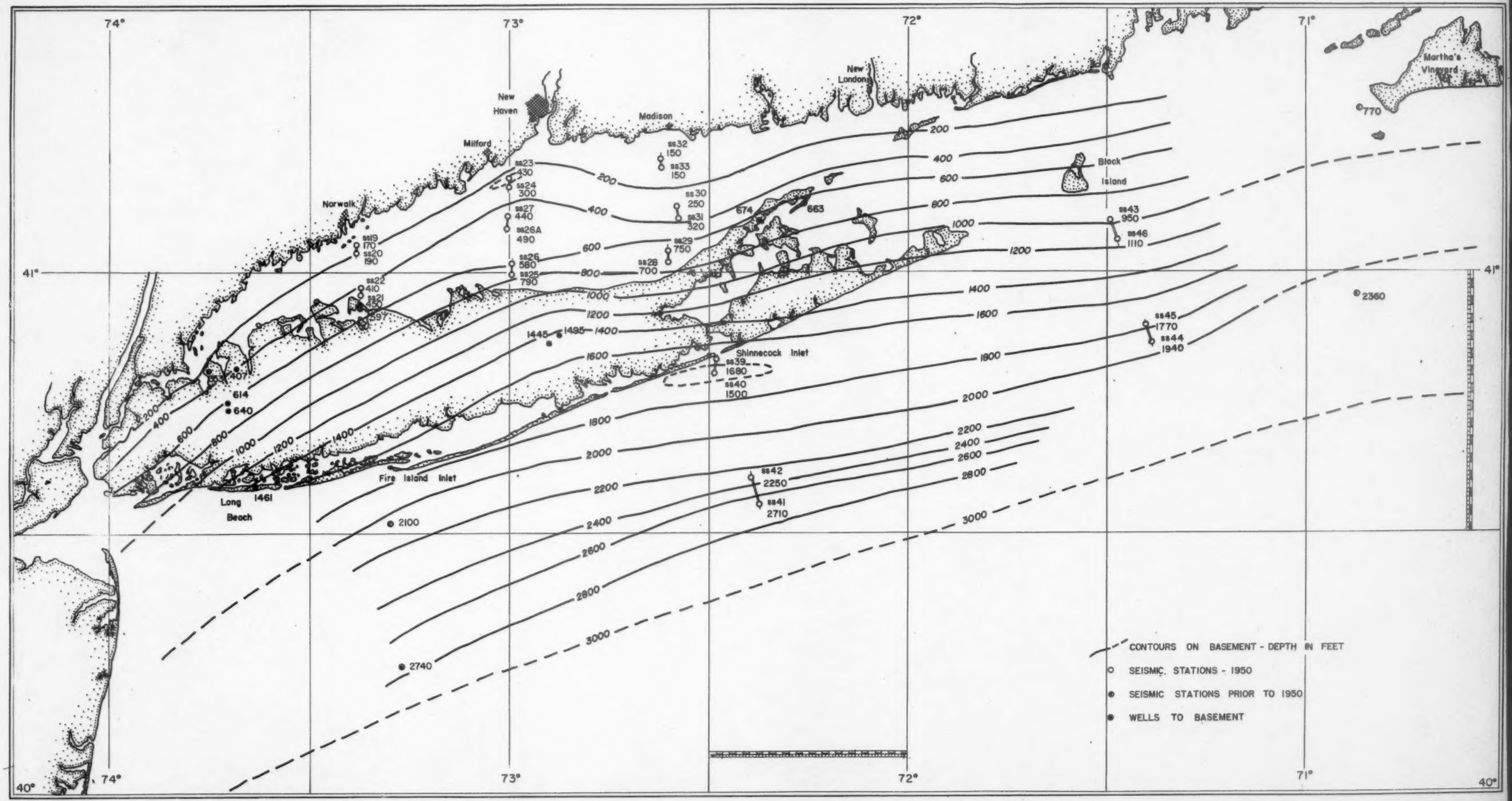
Carolina Bays and Their Origin. By W. F. Prouty

Deformation of Yule Marble: Part IV. By David T. Griggs *et al.*



BASEMENT CONTOUR MAP OF LONG ISLAND AREA

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 62, PP. 1287-1296, 5 FIGS., 2 PLS. NOVEMBER 1951

GEOPHYSICAL INVESTIGATIONS IN THE EMERGED AND SUBMERGED ATLANTIC COASTAL PLAIN

PART VI: THE LONG ISLAND AREA

BY JACK E. OLIVER AND CHARLES L. DRAKE

ABSTRACT

A seismic survey consisting of 12 reversed refraction profiles was carried out in the waters around Long Island. A 200-foot interval contour map of the crystalline rock surface is presented. This surface is approximated by a plane dipping gently south to southeast. Relief of the order of 200-300 feet is indicated. The mean velocity of sound in the basement rocks is 18,400 feet/sec. (5.6 km/sec.). Two other seismic horizons were identified, one termed unconsolidated sediments having a mean velocity of 5400 feet per second (1.65 km/sec.) and a second termed semi-consolidated sediments with a mean volocity of 6500 feet per second (2.0 km/sec.). The latter is found only to the south and southeast of Long Island.

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INTRODUCTION

During the summer of 1950, the depth of basement under Long Island Sound and offshore Long Island was studied using the seismic refraction technique. There were two purposes: (1) to add further information to a regional program of mapping the subsurface basement at the continental margin (Ewing *et al.*, 1937; 1939; 1940; 1950), and (2) to aid in ground water reserve studies of the area.

Eight reversed refraction profiles were carried out in Long Island Sound (Pl. 1), two on a line running southerly from Norwalk, Conn., three south of Milford, Conn., and three south of Madison, Conn. Four reversed profiles were run off the southern coast of Long Island, two south of Shinnecock Inlet, and two south of Block Island.

ACKNOWLEDGMENTS

This project was carried out by the Lamont Geological Observatory of Columbia University under contract with the Office of Naval Research. Explosives were kindly furnished by the Bureau of Ordnance of the U. S. Navy.

Dr. Maurice Ewing was the project director

and Dr. J. L. Worzel the immediate supervisor. W. Beckmann, E. Smith, M. Cassidy, and T. Aldrich participated in the field work.

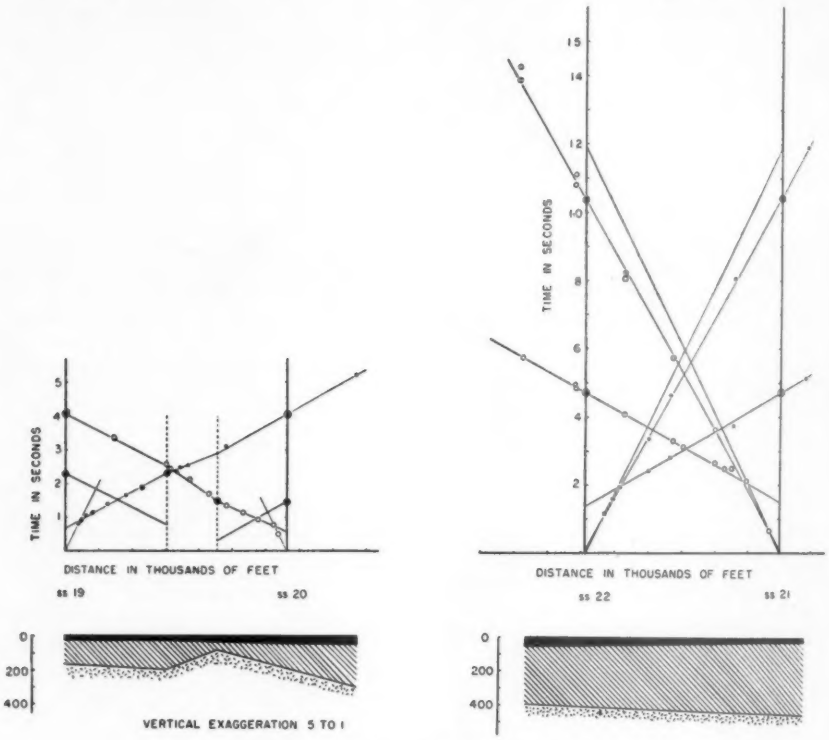

FIGURE 1.—TRAVEL TIME CURVES—NORWALK LINE
August 8–9, 1950

Dr. W. Taylor Thom and Dr. Meredith Johnson were kind enough to critically review the basement results prior to publication.

LOCATION OF STATIONS

The lines of profiles were chosen to give uniform areal coverage between lines of previous stations (Ewing *et al.*, 1950) (Pl. 1). Circles on the map indicate positions of the receiving boat; lines indicate the directions of the shots.

Positions at sea were obtained from horizontal sextant angles, from compass bearings, and by dead reckoning. The first method is the most accurate but suffers most from poor visibility. Stations 19, 20, 32, 33, 39, 40, 43, 46 are well determined by this method. Maximum error of position is estimated at 200–300 feet. Stations 21, 22, 23, 24, 25, 26 were located under more adverse weather conditions. Maximum error is estimated at 1000–2000 feet. Stations 26A, 27, 28, 29, 30, 31, 41, 42, 44, 45 were located by dead reckoning. Maximum error is estimated at ½ to 1 mile. Because of the gentle dip of the basement, an error in the position of a station of the order noted would in no case greatly affect the location of the present contours.

METHOD OF INVESTIGATION

The standard seismic refraction technique was employed (Ewing *et al.*, 1937). Two hydrophones at intermediate depths and a geophone on the bottom were the listening devices. High

FIGURE 2.—TRAVEL TIME CURVES—MILFORD LINE
August 10–11, 1950

FIGURE 3.—TRAVEL TIME CURVES—MADISON LINE
August 12–13, 1950

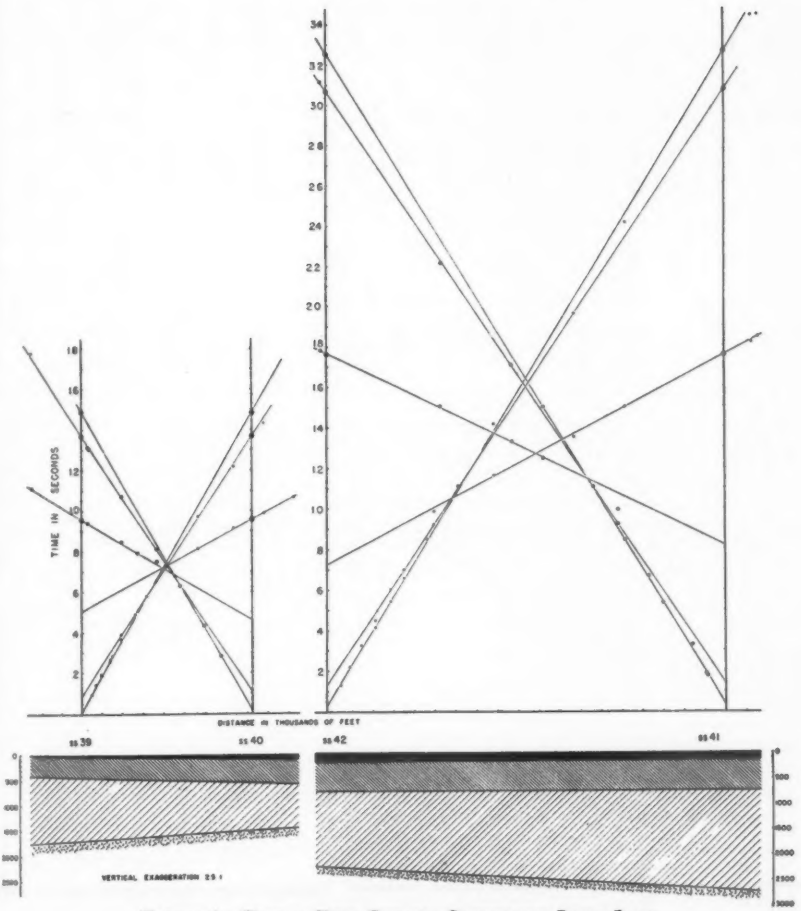

FIGURE 3.—TRAVEL TIME CURVES—MADISON LINE
August 12–13, 1950

FIGURE 4.—TRAVEL TIME CURVES—SHINNECOCK INLET LINE
August 24–25, 1950

frequency traces from the hydrophones were used to detect the first water arrival which gave the distance from the shot. An ordinary, prospecting type, 12-channel recording oscillograph was used. Two of the amplifiers were modified to pass high frequencies.

Timing lines were placed on the record by interrupting a light beam with a synchronous motor whose rate was controlled by a tuning fork. Checks with radio station WWV showed errors in this system to be negligible.

Shots were fired electrically and the shot instant was transmitted to the recording boat by FM radio. This circuit was checked daily by firing a detonator near one of the hydrophones. For short distances half-pound blocks of TNT provided sufficient acoustical energy, while for longer distances tetrytol was used in quantities up to 24 pounds.

Two sample records are shown in Plate 2.

INTERPRETATION OF DATA

The data are exhibited in the form of travel time curves (Figs. 1–5). With the exception of the curves for the Norwalk line, segments corresponding to the water arrival have been eliminated, for this velocity was used to obtain the

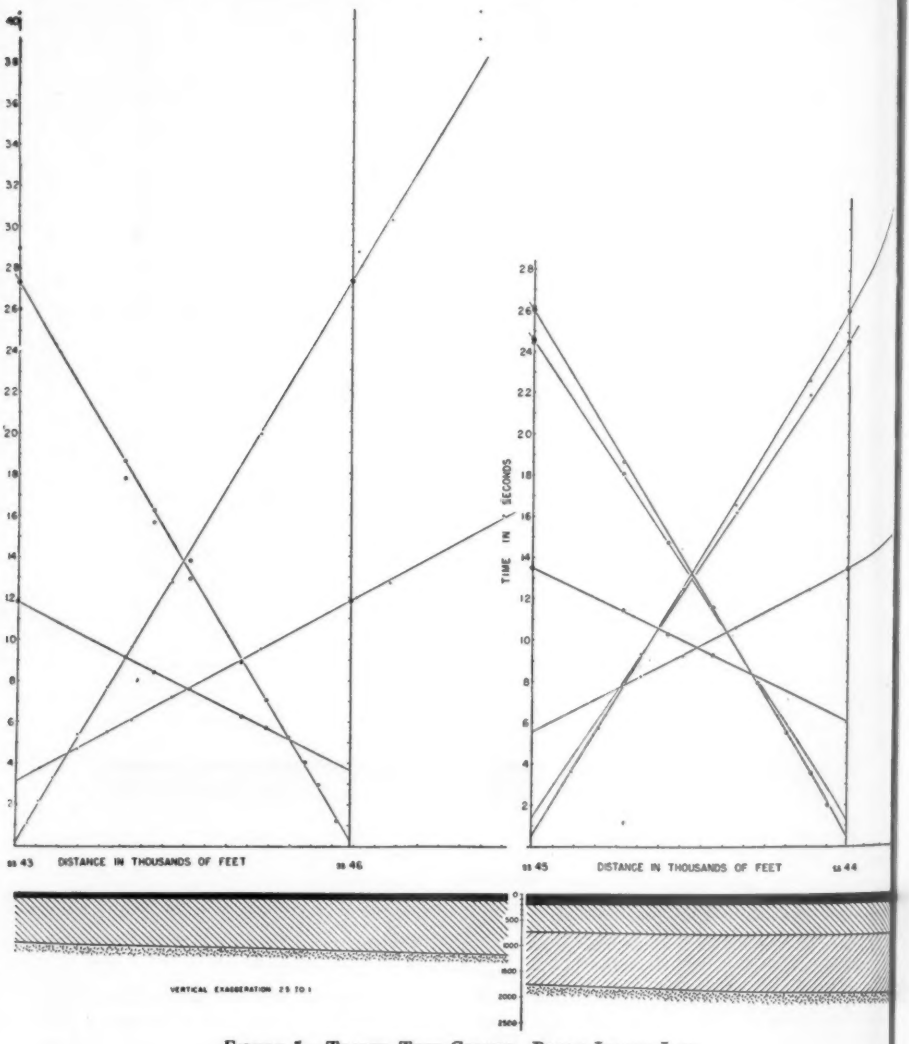

FIGURE 5.—TRAVEL TIME CURVES—BLOCK ISLAND LINE
August 26–27, 1950

distance. Table 1 contains a list of equations of the segments of the travel time curves. There is a maximum of four layers. These have been designated, as in Part V, as water, unconsolidated sediments, semiconsolidated sediments, and basement.

The method of calculation of depth, dip, and velocity of the layers from these equations has been described in Ewing, *et al.* (1939) as well as in various texts on explosion seismology.

The velocity of sound in water was obtained from the temperature and salinity data of Riley (1948). In all cases the velocity varied less than 0.5 per cent from 4950 feet per second so that figure was used in all calculations.

Suitable corrections were made for the depth

TABLE 1—TRAVEL-TIME DATA AND COMPUTED DEPTHS

Station No.	Equations of Travel Time Curves				Velocity (Ft/Sec)			Slope of Basement
	Water	Unconsolidated Sediments	Semiconsolidated Sediments	Basement	Unconsolidated Sediments	Semiconsolidated Sediments	Basement	− Indicates reversal of regional dip
19 A	T = x/4950			T = .067 + x/18450	4950		19125	34′
20 A	do			T = .078 + x/19850				
19 B	do			T = .078 + x/14700	4950		18450	4° 12′
20 B	do			T = .032 + x/25350				
19 C	do			T = .032 + x/18100	4950		19725	1° 20′
20 C	do			T = .073 + x/21650				
21	do	T = .006 + x/5720		T = .150 + x/18250	5725		17650	43′
22	do	T = .010 + x/5725		T = .137 + x/17050				
23	do	T = .003 + x/5260		T = .154 + x/18375	5260		17400	−57′
24	do	T = .004 + x/5260		T = .098 + x/16550				
25	do	T = .008 + x/5540		T = .273 + x/19680	5550		17900	1° 56′
26	do	T = .017 + x/5560		T = .203 + x/16380				
26 A	do	T = .006 + x/5100		T = .186 + x/19100	5100		18650	22′
27	do	T = .008 + x/5100		T = .167 + x/18250				
28	do	T = .009 + x/5520		T = .244 + x/17575	5520		18000	−28′
29	do	T = .010 + x/5520		T = .260 + x/18475				
30	do			T = .096 + x/17325	4950		17800	27′
31	do			T = .124 + x/18300				
32	do			T = .058 + x/17225	4950		17225	0
33	do			T = .059 + x/17225				
39	do	T = .005 + x/5580	T = .082 + x/6460	T = .505 + x/18275	5590	6490	17425	−1° 33′
40	do	T = .016 + x/5600	T = .106 + x/6520	T = .461 + x/16625				
41	do	T = .032 + x/5860	T = .134 + x/6560	T = .816 + x/20125	5860	6560	19375	45′
42	do	T = .035 + x/5860	T = .133 + x/6560	T = .684 + x/18700				
43	do	T = .019 + x/5840		T = .313 + x/17925	5850		18625	32′
46	do	T = .026 + x/5860		T = .368 + x/19350				
44	do	T = .046 + x/5880	T = .136 + x/6480	T = .604 + x/20025	5880	6470	19450	20′
45	do	T = .046 + x/5880	T = .128 + x/6460	T = .533 + x/18925				

of the shot, the hydrophones, and the geophone. Shot depth was calculated from the bubble pulse interval (Ewing *et al.*, 1946) except in shallow water (less than 50 feet) where the shot was assumed to lie on the bottom.

All computations are straightforward with the following exceptions:

Profile 19–20

(1) No intermediate layer arrival was observed. Since profiles in near-by locations have sediment velocities very near but slightly greater than the speed of sound in water, it was assumed for this case that sediment velocity equalled that of sound in water. A lower velocity, also unobservable, would make the basement depth less.

(2) A break in the segment of the curve (Fig. 1) corresponding to basement showed there must be serious deviation from the assumed plane surface. The configuration of the basement was approximated by breaking the problem into three parts by inserting fictitious stations at the breaks in the curves. This method is described in Part V. The number of points on this curve is insufficient for an accurate determination of the surface of the crystalline basement, but it is felt that a reasonable approximation is achieved by the solution presented.

Profiles 28–29, 30–31

No sediment velocity was detected for these stations, so the above assumption was made with identical reasoning.

Because of the well-known possibility of masked or low velocity layers, an accuracy in depth greater than 10 per cent is not claimed.

Discussion of Results

Plate 1 shows a set of contours drawn on the basement surface from the seismic results and the few wells available in eastern Long Island. All well data and the contours west of the 1461-foot well on Long Beach are taken from Suter *et al.* (1949). The reader is referred to his report or to that of Delaguna and Brashears (1948) for a more detailed bedrock map of that area. Dashed lines indicate contours from the regional map of Part V.

A first approximation to the basement surface in a plane dipping south to southeast with a slope of approximately 55 feet per statute mile, less than 1°. Individual profiles, however, show some variation from this plane. Profile 19–20 is the most obvious example where the slope of one segment is of the order of 4° and is reversed, that is, the slope is opposite to the regional dip. This feature is not shown on the map because of its small horizontal scale. See instead the cross section (Fig. 1). None of the other profiles show slopes greater than 2°. However, the slopes of profiles 23–24, 28–29, 39–40 are also reversed.

Some ambiguities arose in drawing the contours. Profile 23–24 has a reverse slope and a depth greater than might be expected from the adjoining stations. This has been interpreted as due to a depression near station 23. A similar situation occurs at profile 39–40 where a buried hill has been located in the basement near station 40.

Near station 21 (depth 450 feet), a well has been drilled on Eaton's Neck with bedrock reported at 597 feet. Although the difference in depth might be explained by relief on the basement surface, Suter notes that the well report is of poor reliability. Therefore, no account has been taken of this well in drawing the contour map.

The velocity of the basement varies between 17,250 feet per second (5.3 km/sec.) and 19,700 feet per second (6.0 km/sec.). There appears to be a trend toward higher velocities where the surface of the basement is deeper, but because of the limited number of samples, it is felt that no significance can be attached to this at present. From the heterogeneous surface geology of Connecticut over a similar area, one would not expect a very constant or a very regularly progressive velocity.

The velocity of the unconsolidated layer ranges from 4950 to 5880 feet per second with the larger numbers again appearing offshore. This is attributed to increased compaction.

At profiles 39–40, 41–42, and 44–45, three of the four off-shore profiles, the upper sedimentary layer thins and a fourth layer was detected overlying the bedrock and having a velocity ranging from 6470 to 6560 feet per second. This layer has been termed semi-consolidated sediment as in Parts IV and V. The velocity agrees

well with those found at similar basement depths on the Cape May, N. J., line of Part IV.

Geologic Implications

The following is a brief summary of the geology of the Long Island area pertinent to the present problem along with the implications of the data. (For a more complete account of the geology, see Suter, 1949.)

The basement is probably of Paleozoic age, consisting mostly of gneisses and schists with occasional pegmatitic and granitic intrusives. In Permian or early Triassic time the crystalline surface was peneplained. This was followed by the deposition of the Triassic red beds and trap rock of New Jersey and Connecticut which in turn were eroded to a nearly level surface called the Fall Zone peneplain. Remnants of the Triassic are found in a long valley running north through New Haven. The possibility that this valley continues under the Sound and under Long Island itself has been suggested by some geologists. The observed basement velocities are strong evidence against the presence of Triassic beds beneath the line of profiles.

In the middle of Cretaceous time, the Fall Zone peneplain was tilted toward the southeast and lowered with respect to sea level in the Long Island area. Toward the northwest, the peneplain lay above sea level and the erosion which followed deposited the Cretaceous sediments on the crystalline surface. These are divided into the older Raritan formation and the Magothy (?) formation. All formations converge shoreward. The lower member of the Raritan formation is the Lloyd sand which wedges out toward the northwest in Kings and Queens counties. Because of this, DeLaguna has suggested the possibility of older Cretaceous beds to the southeast. These may be indicated by the 6500 foot per second layer found at the offshore stations, although the higher velocity might also be attributed to conditions of sedimentation causing a facies change or to compaction.

At the close of Cretaceous time, the land was again raised and possibly tilted to the southeast. The basin that is now Long Island Sound was presumably formed by erosion in Tertiary time.

The Pleistocene brought mostly glacial type sediments, which cover the greater part of Long Island. Relief of the shallow basement in western Long Island has been attributed to glacial scouring in this period. Such scouring might also be the cause of the relief on profile 19–20. However, the reversal of slopes on the other profiles, particularly 39–40, cannot be explained in this manner. Dr. W. T. Thom (1946), basing his ideas on well log studies of similar areas along the coast, has suggested that, prior to the subsidence of the Fall Zone peneplain, the region was raised long enough to allow considerable erosion in weaker rock. Although the present investigation seems to indicate that this is the case, a more thorough study on a local scale is needed before any conclusions may be drawn.

Relief under the Atlantic coastal plain of the order of a few hundred feet has also been reported by Woollard in New Jersey (Pt. III) from land seismic data, and by Mathews (1932) in a basement relief map taken from well data in the Baltimore, Maryland, area. Richards (1950) reports granite outcrops east of the Fall Line in Maryland in a region where the general depth to basement is about 400 feet.

Summary

(1) The seismic data coupled with the wells to bedrock in eastern Long Island indicate that the basement surface may be approximated by a plane dipping south to southeast at about 55 feet per mile.

(2) Relief of at least 200 feet is found on the basement surface including areas that underlie Cretaceous sediments. Similar relief has been found elsewhere under the Atlantic Coastal Plain.

(3) A single seismic horizon designated as unconsolidated sediments is found between water and basement over most of the area. On three of the offshore profiles another horizon called semi-consolidated sediments with a slightly higher velocity overlies the basement.

(4) The mean velocities are: unconsolidated sediments, 5400 feet per second (1.65 km/sec.); semi-consolidated sediments, 6500 feet per second (2.0 km/sec.); and basement, 18,400 feet per second (5.6 km/sec.).

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, FEBRUARY 23, 1951.

LAMONT GEOLOGICAL OBSERVATORY CONTRIBUTION No. 39

LONG ISLAND

ss 26A SHOT
8950 FEET 3 PO

INSTRUMENT	GAIN	FILTER
TIME AFTER SHOT → +.038		
GEOPHONE	HIGH	2-120 cps
RADIO - TIME BREAK		
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GEOPHONE	HIGH	2-46
GEOPHONE	LOW	2-46
GEOPHONE	HIGH	59-120
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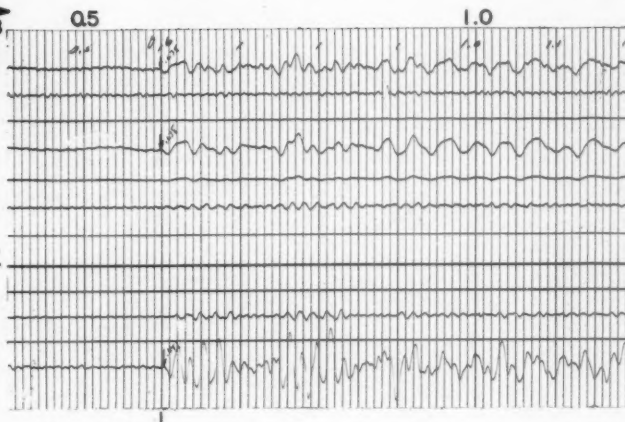

OFFSHORE LONG

ss 39 SHOT
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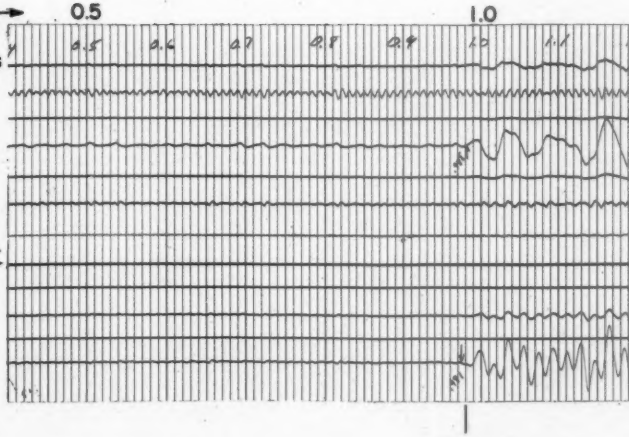

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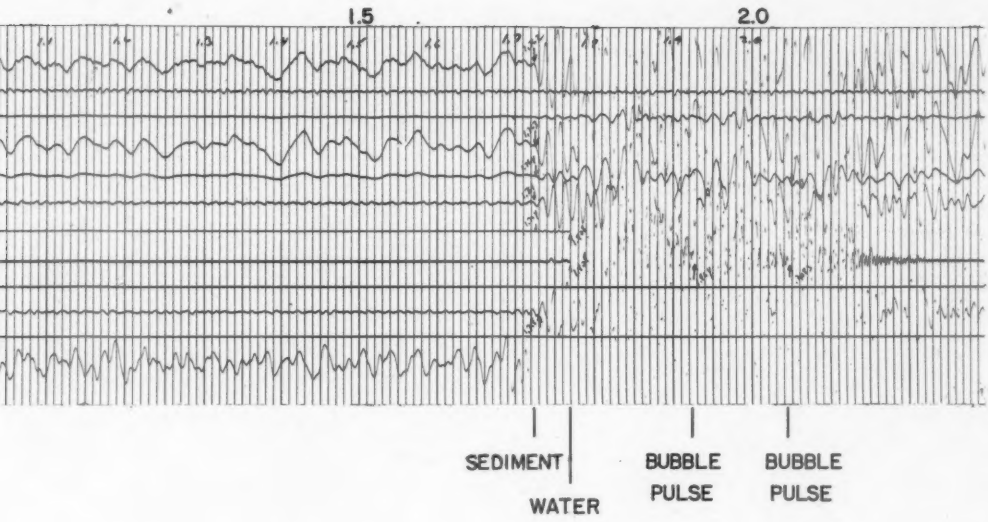

LONG ISLAND

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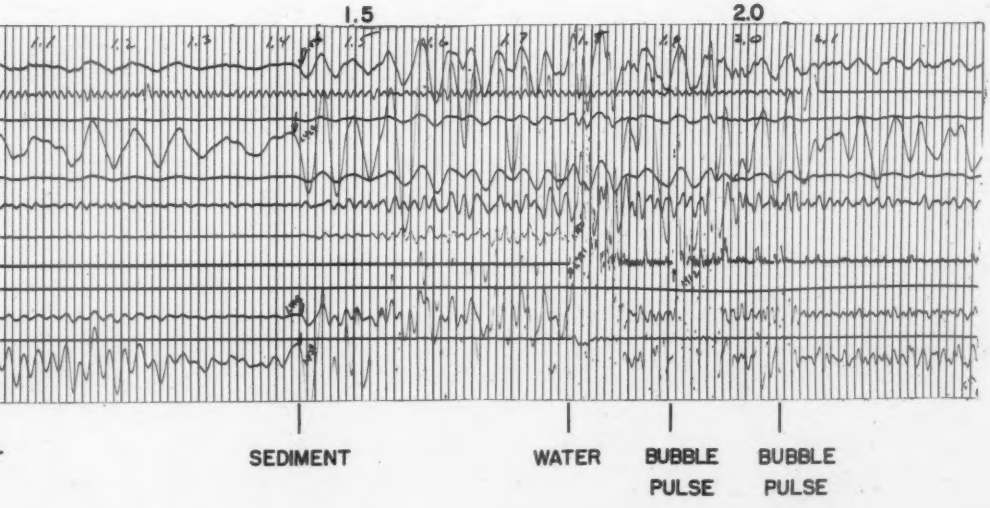

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 62, PP. 1297-1330, 6 FIGS., 2 PLS. NOVEMBER 1951

STUDY OF SOME BERMUDA ROCK

BY FRED FOREMAN

ABSTRACT

A petrologic study of the subsurface clays and marine limestones from the Castle Harbour area; the weathered and water-worn volcanics from the Gibbs' Hill bore hole; a sample from the Prospect Military Well; a conglomerate sample from the Hard Bermuda Limestone, all from the Bermuda Islands, is described.

All allogenic mineral species found in the sediments are also found in the volcanics; similar minerals were reported by Sayles (1931) from the surface eolianites and soils of the island. The volcanics carry minerals not found in the sediments, but these are minerals whose stability is lowest under weathering conditions.

A chemical as well as a textural and a petrographic analysis is given of the most interesting and important sediment, the Primary Red Clay. This clay is a type of lateritic soil, the result of sub-aerial, tropical, humid, weathering of the igneous rocks of the island. A distinctive feature of this clay is the high content of phosphatic material. Part of this phosphate is in the form of collophanite; the rest seems to be an actual constituent of the clay. This phosphate was added to the clay after the clay was formed, when it was covered by the marine waters of a lagoon.

No exact age for the clays and marine limestones was reached, but they would appear to be of late Tertiary age.

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Introduction

Although Bermuda lay south of any of the Pleistocene ice sheets, the glacial and interglacial stages of that time were accompanied by great changes in sea level, ocean currents, and climate, and consequently in the type of flora and fauna (Bryan and Cady, 1934). These changes were directly reflected in the type and amount of sedimentation. During times of glaciation, the corals disappeared, the level of the ocean dropped 75–90 meters (Daly, 1934), and the greater part of the bank was exposed to sub-aerial erosion and deposits of calcareous eolianites were formed. During the warmer interglacial periods with their higher sea level and climatic conditions much like those at present, the fossil soils accumulated. The eolianites and soils were correlated by Sayles (1931) with the glacial and interglacial stages and found to correspond with all the known glacial and interglacial stages except possibly the Nebraskan and Aftonian which were either represented by the Walsingham eolianite or were not present or had not been exposed.

The nature of the subsurface rocks was unknown until Pirsson (1914) reported on the cuttings from a churn drill boring in the Gibbs' Hill area. He found chalky limestone rock to a depth of 380 feet (245 feet below sea level) and underlain, first, by more than 200 feet of weathered volcanic material and then by 100 feet of rounded and waterworn volcanics; below these, the drill penetrated 700 feet into basaltic lavas.

During the construction of the air base at Castle Harbour and Ferry Reach, 1941–1943, other subsurface rocks were found. Hilary B. Moore and Doris M. Moore (1946) reported on the type and sequence of faunas from these and they were of the opinion that these rocks were older than any studied by Sayles (1931).

This paper is a report based on textural and petrographic analyses of subsurface rocks of Bermuda from the following localities: the air base at Castle Harbour and Ferry Reach; the weathered and waterworn volcanics of the Gibbs' Hill bore hole; a limestone conglomerate from the Town Cut Channel St. Georges Harbour; and a calcareous soil from the Prospect Military Well.

Acknowledgments

Mr. H. C. Stetson at Harvard College suggested this study and arranged for the shipment of specimens; the Castle Harbour sediments through Dr. H. B. Moore, Bermuda Biological Station; and the bore hole samples through Professor A. Knopf of Yale University. The writer is indebted to him also for suggestions and critical help with the manuscript.

Dr. H. B. Moore gathered the sedimentary samples and gave the field description of these. Professor G. P. Woolard was kind enough to

give additional data and interpretation regarding the gravity anomalies found on the islands; the Research Laboratory of the Reynolds Metals Company of Little Rock, Arkansas, through the good offices of Mr. Robert Schrock, were kind enough to make the chemical analysis of the Primary Red Clay.

Professor E. S. Larsen at Harvard College gave continuing help and criticism through the investigation and preparation of the manuscript.

Regional Setting

The size and topography of the present Bermuda Islands and their position on the Bermuda Banks and relationship to neighboring lands has been fully given by Verrill (1905), Sayles (1931), Livingston (1944), and others. These islands have a total area of little less than 20 square miles and are situated on the south and southeast sides of the Bermuda bank. This bank is roughly elliptical in shape, about 200 square miles in area, and covered by a rather uniform depth of water of about 60–70 feet and fringed by a reef whose outer edge is from 1 to 3 miles inside the outer margin of the bank. The bank is comprised of a series of calcareous formations overlying a volcanic pile which seems to have been eroded by the waves, likely during the Tertiary, to a depth of some 250 feet (Woolard and Ewing, 1939).

These Islands have some unique features that are of interest in sedimentology. The nearest land is over 600 miles away and the ocean nearly 3 miles deep. Allogenic minerals found in the sediments were either derived from the underlying volcanics or carried by unusual transporting agents, such as birds, sea weed, jelly fish, wind, etc.

Methods of Analyses

Present-day methods of sampling in sedimentation attempt to secure a representative portion of the sediment in the region of sampling. This is necessary if statistical methods of analysis and interpretation are used. The samples studied in this report cannot fully meet the above requirement, but, as they are the only known rocks from the subsurface formations, any information winnowed from them would help in reconstructing the past history of the island.

The clays and other unconsolidated samples were disaggregated by standard methods. However, the finest clay fractions showed some flocculation which was impossible to prevent. Soil scientists have found that the dispersion of the finer clay fraction in sediments is influenced by both the cations and the radicals in it. The effect of the sesquioxides, especially alumina, has been discussed by Robinson (1933) and the effect of the carbonate radical by Baver (1940). The effect of such large amounts of phosphate and titania as were found in these clays is not known, but they were likely responsible for the difficulty in trying to obtain dispersion. To subject these sediments to an acid treatment strong enough to dissolve out the carbonate and phosphate would have also affected the clay minerals and the iron oxides, and it was decided that the standard method gave as true a picture of the texture of the clay as is possible at this time.

The Brick, Chert, and Phosphatic pebbles each contained such a large amount of phosphate that the analysis was not carried beyond the one-sixteenth millimeter sieve size.

It was necessary to dissolve the phosphate of the "Chert" and the phosphate pebbles as well as the carbonate of the marine limestones in dilute hydrochloric acid before the insoluble minerals could be studied. The residues from these rocks were sieved but no pipette analysis was run.

The minerals in some of the samples, notably in the Primary Red Clay and its derivatives, were coated with oxides of iron. This hindred identification and also light and heavy mineral separation. This coating was readily dissolved by treating the minerals with a weak solution of HCl and $SnCl_2$ and heating on a steam bath for an hour or two (Tester, 1931).

Petrographic methods were standard; immersion oils were checked by a Zeiss refractometer up to $N = 1.68$ and by the method of minimum deviation above 1.68. Liquid mixtures of sulphur, phosphorus and methylene iodide were used (West, 1936) from 1.78 to 2.06; above 2.06, melts of sulphur and selenium.

Chemical tests for the chromium, titanium, and phosphate (Brush and Penfield, 1926) minerals supplemented the optical determinations. In some cases more complete optical data were obtained by using the double dispersion method of Emmons (1943). Mineral separates of each rock sample where given as weight percentages are considered significant to 0.002 per cent. Except for the "Brick," "Chert" and Phosphate pebbles from the Secondarily Reworked Clay, amounts varying from 200 to 300 grams were used in each analysis. In the small samples of the three exceptions given above between 100 to 150 grams were used. In the sieve and pipette analysis, fractions were weighed to the nearest milligram and the light and heavy minerals separated in each size grade to a tenth of a milligram if less than a gram and a milligram if greater than a gram.

Heavy mineral separation size grades were quartered when necessary by an Otto microsplit (Krumbein and Pettijohn, p. 357) to portions of about 300 grains in the coarse sizes and up to about 1000 grains in the smaller size groups. The proportion of each mineral present in a group was multiplied by its specific gravity and its percentage weight calculated.

For the light mineral separates a somewhat different procedure was used. Each size grade was split, if necessary, to give from an eighth of a gram in the smallest sieve size to a gram in the coarsest. The quartz and mica grains were picked out and weighed and the pellets which made nearly all the fraction were found as the difference, by subtracting the weight of the separated minerals from the initial weight of the group.

The roundness factors were determined by a visual procedure based on the method of Russell and Taylor (1937). In each case the outline of the grain was compared to the outline on the standard chart showing angular, sub-angular, sub-rounded, rounded, and well-rounded grains. The numerical method of tabulating these was not used because it was apparent that solution effects were important in these sediments, and it seemed better to use the descriptive terms rather than the number system to describe the grains.

Types of Rock

Clay (Primary Red Clay)

"Clay" was the term used by Moore and Moore (1946), but "Primary Red Clay" will be used in this paper. It was used by Moore in his letters to the author and its descriptive value gives it a more specific meaning than the general name "Clay." The Primary Red Clay is obviously the most important sediment of the group and was evidently the source of the next three, the Secondarily Reworked Clay, the Chert, and the Brick.

This sediment was a rather hard reddish-brown clay containing an occasional small fragment of white to gray angular limestone. There was no indication of stratification. When dry, the clay was well indurated and was broken with difficulty with the fingers; when wet, it was plastic and dispersal required considerable stirring. This clay was evidently laid down under marine water, as only foraminifera and sponge spicules were reported to be found in it by Moore and Moore (p. 209).

Textural analyses are given in Table 1 after the fragments of white limestone were picked out. These are reported separately. Percentages of the minerals in each of the size grades are given in Table 2.

Description of Minerals in the Primary Red Clay

Quartz.—This mineral can best be discussed if divided into two groups, group A, grains

Plate 1.—PHOTOMICROGRAPHS

Figure 1. Quartz Grains

½–¼ mm. grade size.

Figure 2. Pellets

½–¼ mm. grade size.

Figure 3. Perovskite

Note the partial coating of leucoxene (white) on many of the grains and the striations on uncoated surfaces due to intrastratal solutions. ½–¼ mm. size grade.

Figure 4. Clay

Dark bodies in clay are due to local concentration of ferric oxide, these bodies called oölites in text. The larger oölite shown has diameter of approximately 20 microns.

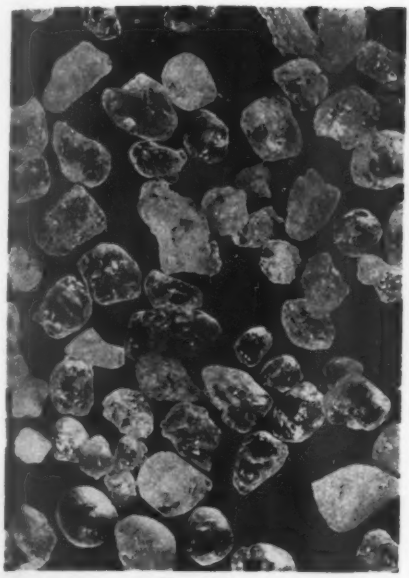

FIGURE 1

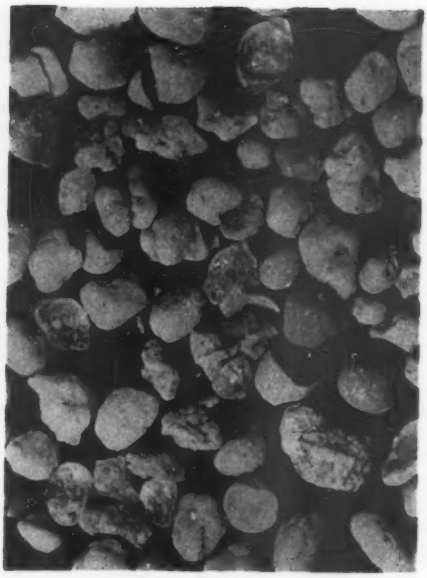

FIGURE 2

FIGURE 3

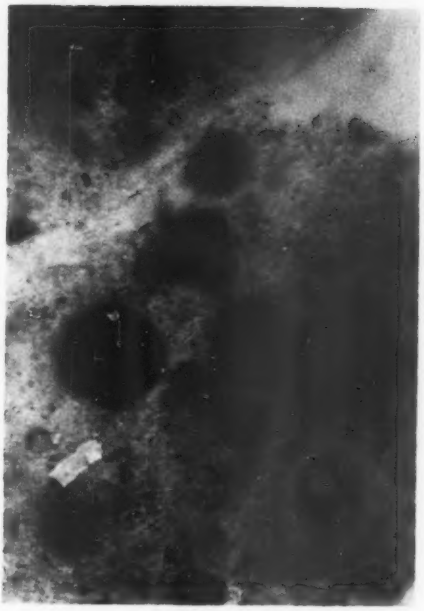

FIGURE 4

PHOTOMICROGRAPHS

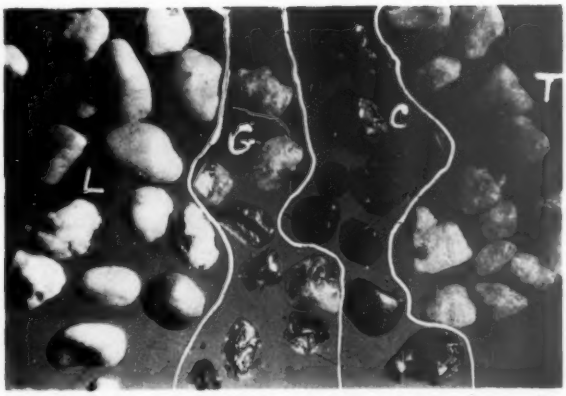

FIGURE 1

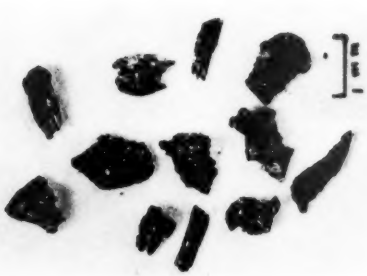

FIGURE 2

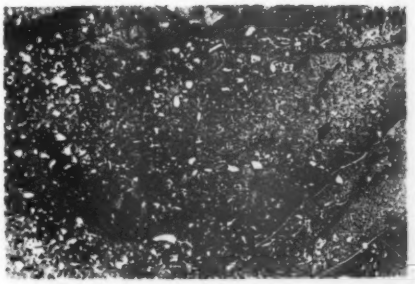

FIGURE 3

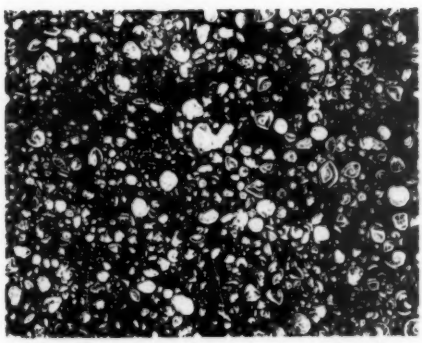

FIGURE 4

FIGURE 5

PHOTOMICROGRAPHS

greater than one-quarter mm., and group B, grains less than one-quarter mm.

GROUP A: The quartz grains generally showed some degree of rounding: of 300 particles observed, 28 per cent were angular, 41 per cent sub-angular, 22 per cent sub-rounded, 7 per cent rounded, and 2 per cent well-rounded. About a third of these grains had pitted and etched surfaces which were invariably present on the rounded and well-rounded grains as well as on most of the sub-rounded grains, but only occasionally on the sub-angular and angular grains (Pl. 1, fig. 1). However, even in the re-entrant angles of some of the angular grains, this same pitting and etching was present. Many of the larger grains were very irregular in shape, showing cavities and vug-like holes as though they came from secondary quartz, and a few had platy surfaces, possibly due to the development of imperfect cleavage.

About 90 per cent of all the grains were clear, but some were milky and others yellow-brown to red. Others were dark from dusty inclusions, and an occasional grain seemed to be made of silt stone, always well rounded. Of the clear grains, less than 10 per cent showed undulose extinction.

GROUP B: The amount of rounding was defi-

TABLE 1.—(COLUMNS 1–6) TEXTURAL ANALYSES OF BERMUDA CLAYS AND SOIL FROM PROSPECT MILITARY WELL (7)

Diameter (in mm.)	1	2	3	4	5	6	7
2–4	0.88						
1–2	0.54	0.75		0.02			7.5
1/2–1	1.38	4.90	0.55	0.08	0.07		19.3
1/4–1/2	3.08	6.31	0.60	0.10	0.17		26.6
1/8–1/4	1.76	3.60	1.56	0.33	0.49	0.11	7.7
1/16–1/8	0.75	4.62	1.96	2.38	0.46	0.13	2.8
1/32–1/16	1.0	4.6	1.6				3.2
1/64–1/32	3.5	9.8	3.1				2.4
1/128–1/64	3.0	8.6	7.1				27.2
1/256–1/128	5.5	3.2	3.8				3.1
1/512–1/256	20.4	4.1	4.3				
1/1024–1/512	31.5		7.3				
Material less than smallest size shown above	26.30	48.80	68.20	96.89	21.60	0.97	
Total	99.59	99.28	99.87	99.80	22.79	1.21	99.8
Amount soluble in HCl	13.2	31.1	6.8	74.5	77.21	98.79	99.9

Column 1 Primary Red Clay; Column 2 Brown Phase of Secondarily Reworked Clay; Column 3 Gray Phase of Secondarily Reworked Clay; Column 4 "Brick"; Column 5 "Chert" (residue after HCl); Column 6 Phosphate Pebbles (residue after HCl); Column 7 Prospect Military Well.

PLATE 2.—PHOTOMICROGRAPHS

FIGURE 1. LEUCOXENE (L), GARNET (G), CHROMITE (C), TITANITE (T)
$\frac{1}{2}$–$\frac{1}{4}$ mm. size grade.

FIGURE 2. AUGITE
Showing spiny nature of grains.

FIGURE 3. COLLOPHANITE
Thin section of "Brick" phosphate clay showing shape and distribution of collophanite grains (white). Plane transmitted light, × 10.

FIGURE 4. SANDSTONE ROCK
Foraminifera tests and fragments in dark fine-grained matrix, × 10.

FIGURE 5. AUGITE AND CALCITE IN WEATHERED IGNEOUS PEBBLE
Broken augite phenocrysts (A) and calcite patches (C) in a dark fine-grained matrix, × 15.

nitely less in this group. An eighth of a millimeter was near to the size where rounding of the grains ceased to be apparent. Some of the grains between a quarter and an eighth of a millimeter showed partial rounding, but all less than an eighth of a millimeter were angular. Of 400 grains studied, 81 per cent were angular, 17 per cent sub-angular, and 2 per cent sub-rounded. As in Group A, most of the grains (86 per cent) were clear; the rest were either milky, iron stained, or dusky.

TABLE 2.—PRIMARY RED CLAY*

Size Grade in mm.	1–½	½–¼	¼–⅛	⅛–1/16	Total
Quartz	0.180	0.180	0.140	0.130	0.630
Zircon	0.044	0.200	0.280	0.068	0.592
Chromite	0.052	0.540	0.340	0.102	1.234
Magnetite	0.012	0.030	0.022	0.061	0.125
Perovskite	0.530	0.570	0.430	0.030	1.560
Leucoxene	0.040	0.180	0.270	0.058	0.548
Titanite	—	0.030	0.051	0.012	0.093
Garnet		0.020	0.033	0.007	0.060
Augite	0.024	—	0.011	—	0.035
Epidote		—	—	—	—
Feldspar				—	—
Pellets	0.487	1.280	0.200	0.270	2.244
Total	1.369	3.030	1.757	0.738	

* Percentages of Minerals in Size Grades based on total weight of sample. Where a dashed line is present mineral occurs but is less than 0.001 per cent.

Pellets.—In the Primary Red Clay and the Brown Phase of the Secondarily Reworked Clay, it was not possible to separate certain of the grains into groups. Some of these grains were of iron oxide, others of phosphatic, and still others of calcareous material, but most of them were a mixture of all three, a mixture that seemed to range continuously between the three end members. These variations in chemical composition were reflected in variations in color, in specific gravity, and in chemical reaction that differed by such slight increments it was thought best to group them all under the term Pellets (Pl. 1, fig. 2).

However, in the Gray Phase of the Secondarily Reworked Clay, the greater part of the grains were soluble and light buff or white in color, the rest having the characteristics of the iron oxide, and are therefore given as separate groups. From those consolidated samples that were treated with dilute acid, only the iron oxide pellets are reported since they were the only members of this group unaffected by the acid.

Chromite.—The chromite grains were black and opaque, and either octahedral or fragmentary in shape; they were not attracted by the hand magnet and gave good chemical tests for chromium in borax and salt of phosphorus beads. Small splinters showed a slight transparency and N= 2.07.

The octahedrons usually had slightly rounded edges but some were quite euhedral; the number of octahedrons increased from 1.5 per cent of the crop in those greater than half a millimeter to 4 per cent of those between an eighth and a sixteenth of a millimeter (Pl. 2, fig. 1). The fragmentary grains were mostly rounded to sub-rounded when greater than a quarter of a millimeter and sub-rounded to angular when less.

Magnetite.—Magnetite appeared chiefly as rusty brown but occasionally as shiny black, sub-angular to sub-rounded grains. This rusty effect was evidently due to oxidation, but the grains were still very magnetic. Most of them when broken showed a black unweathered core: a few of them were rusty all the way through but still strongly attracted by the hand magnet. These rusty grains were irregular in shape and quite angular. A few of the unweathered grains showed crystal form, either the octahedron or the dodecahedron.

Zircon.—Zircon was mostly in the quarter to an eighth of a millimeter grades and made altogether nearly half of 1 per cent of the total sediment. These grains were translucent (65 per cent) to clear (35 per cent) except for a rare grain of very pale yellowish-white. Many of the translucent grains were crowded with very small irregularly oriented inclusions. Some of the larger grains were biaxial with 2V from 8°–12°; none of the grains showed crystal faces. The translucent grains were commonly sub-rounded to sub-angular while the transparent ones were sub-rounded to well-rounded; the proportion of clear grains increased in the smaller grade sizes.

Perovskite.—Perovskite is an uncommon min-

eral in most sediments but may be expected in sediments derived from melilite basalts and other basic felspathoidal rocks. Pirsson (1914) has shown that these rocks were present and were perhaps the dominant igneous rocks underlying the sedimentary cover. The perovskite grains were reddish-brown to brownish-black and always weakly birefringent, although varying in different parts of the same grain, possibly due to twinning. A partial or complete coating with a white to buff opaque layer was common (Pl. 1, fig. 3). This coating was leucoxene and there was every gradation from fresh, uncoated grains through partially coated to those that were totally covered and could only be distinguished from leucoxene grains by crushing in order to expose the perovskite core. Striations were common on the fresh surfaces, especially of the larger grains; these varied in direction in the same grain and seemed to be the external effect of the penetration twinning on the (001) and (110) faces (Dana, 1944).

Titanite.—This other allogenic titanium-bearing mineral, clear to translucent, angular to sub-rounded grains, was commonly honey-yellow but sometimes yellow-green, often with acicular but sometimes with minute irregular dust-like inclusions (Pl. 2, fig. 1). None of these grains showed a leucoxene coating or any sign of weathering or solution effect except possibly the rounding of the grain or the presence of dusty inclusions.

Leucoxene.—This ill-defined mineral, leucoxene, was found in all size grades but reached a maximum in the quarter to an eighth of a millimeter group. The grains were opaque in transmitted light and a dull white to buff, "egg shell," appearance in reflected light (Pl. 2, fig. 1). Its appearance, as noted above, as an alteration product on the perovskite grains would indicate its secondary origin. Except for rare, very minute crystals of what seemed to be brown rutile, no specific mineral could be identified in the leucoxene grains.

Augite.—The augite grains were surprisingly fresh and unaltered, and occurred chiefly as angular cleavage fragments that showed little or no rounding (Pl. 2, fig. 2). Many of them showed spiny, hacksaw terminations. These had been noted before in sediments from the Bermuda area by Larsen (Sayles, 1931, p. 440) and also by Young (1939). The grains usually appeared black, dark brown, or dark green, but in thin fragments were green to light brown. Optically they were much the same with $\alpha = 1.689$, $\beta = 1.695$, and $\gamma = 1.713$, 2V near 60°, with slight pleochroism from green to greenish-brown, maximum extinction of near 42°. There were occasional grains with maximum indices up to 1.724, these were always filled with needle-like dark inclusions which were aligned in two directions at an angle of 65°–70°, and more rarely grains with small extinction angle and optic angle that may be a type of pigeonite. Also a fibrous grain or two was present with lower indices; these may be an alteration product, possibly uralite. No purplish titaniferous variety of augite was found, which was surprising considering the amount of titanium in the source rock and Pirsson's (1914) descriptions of this mineral in the lavas. Young (1939) also reports purplish augite in the deep sea cores taken from the floor of the ocean to the east of the island.

Garnet.—An occasional grain of brown garnet was found, usually clear, isotropic, and angular to sub-angular in shape. The color varied from light to dark brown, the former have an index of refraction of 1.780 and the latter 1.870 (Pl. 2, fig. 1). Much more infrequent than the brown was the rare grain of pink to red garnet. These were angular to sub-angular, clear, and with high luster. R. I. very near 1.800.

Epidote.—Occasional, either as yellowish-green translucent, sub-angular to sub-rounded grains, or as angular, transparent light green with practically no pleochroism.

Feldspar.—Rare grains of feldspar were present, either orthoclase or acid plagioclase, usually oligoclase, and found only as particles less than an eighth of a millimeter in size. The orthoclase was fresh, with good cleavage and usually had many inclusions. The plagioclase was angular and often showed albite twinning.

Silt

The material less than a sixteenth of a millimeter was divided by decantation into a coarse and a fine fraction. In the coarse fraction the minerals were the same as in the one-eighth to one-sixteenth grade size and in about the same proportions, except that zircon was more and

quartz less plentiful. This might have been caused, at least partially, by the difference in specific gravity of the two minerals.

Clay and Colloids

The fine fraction of the Primary Red Clay, separated by decantation from the silt-sized fraction, was allowed to settle and then dried on a steam bath. The upper, finer part of this dried material was shaved off with a knife and contained the clay and colloidal phases of the sample. This fraction was studied at high magnification (× 1000, oil immersion) in oils of differing indices of refraction.

Four phases were observable in this part of the clay: a gel-like apparently amorphous matrix; scale-like to irregular shaped granules, thickly scattered through this matrix; small oolith-like bodies; and grains and fine aggregates of calcite and flakes and fibers of mica-like particles.

The matrix varied from colorless to light yellowish-brown in color, usually isotropic, but sometimes showed a faint opalescent birefringence between crossed nicols. Its index of refraction ranged from 1.580 to 1.648, the indices increasing with the depth of the color.

The granules ranged from an upper limit of about 4 microns to particles too small to be measured. They were isotropic and similar in color range to the matrix but had a higher index of refraction which ranged from 1.66 to 1.78. Generally the index of refraction increased with depth of color but not always. Some colorless granules had an index of refraction as high as the maximum obtained for any of the colored particles. No known isotropic clay minerals have been reported with a refractive index as high as those which these granules showed. Ross and Kerr (1935) found that a halloysite from Alban, Tarn, France, which was dark red from iron oxide, gave N = 1.648, the increase obviously due to this contamination. Winchell (1933) gave the indices for various alumina-silica-hydrogels, in which the index of refraction was a maximum of 1.68 where the ratio of Al_2O_3:SiO_2 was 1:0, and a minimum of 1.48 where the ratio was 0:1. The maximum he gave was close to the minimum found in these granules, and we must conclude that in all probability the high titania and phosphate content of this clay was responsible for its unusually high index of refraction. This problem is discussed in greater detail later in this paper.

Scattered through the matrix also were very small, rounded ferruginous bodies, not hard but still with definite form, in which the concentration of the iron oxide was obviously higher than in the rest of the clay; for want of a better name, these minute accretionary bodies are here called oölites (Pl. 1, fig. 4). They ranged in diameter from 3 to 20 microns and were a deeper red-brown than the rest of the clay. Most of these oölites were the same color throughout, but some showed a concentric pattern, usually with a deep red-brown center which graded rapidly into a zone or zones in which the color varied between a yellowish-brown and a reddish-brown.

Also scattered through the clay were grains and aggregates of minute calcite grains, some of them large enough to identify but most as minute grains which gave an aggregate birefringence effect between crossed nicols. Small lamellae of a micaceous mineral up to 2.5 microns in length were also present in the clay. These showed moderate birefringence and indices of refraction that varied from 1.56 to 1.58. They appeared to be biaxial with small optic angle and are provisionally called gibbsite. It was impossible to judge the total amount of this mineral as it graded into particles too small to be resolved and since they had about the same refractive index as the lower index for the matrix, the mass effect, as with the calcite, was to give a slight lighting of the field between crossed nicols.

Limestone Peboles in Primary Red Clay

In the sample of Primary Red Clay which weighed about 2000 grams were six small, white limestone pebbles. These were picked out but were not reported in the size grades. They were angular and ranged from 7–26 mm. long; their total weight was 12.1 grams. Two thin sections made from the pebbles showed them to be composed of small angular to sub-rounded fragments of shell and limestone material varying from 0.6 to 0.1 mm. in length cemented by clear calcite grains fron 0.03 to 0.005 mm. in diameter. These pebbles seemed to be from a well-cemented eolianite composed of fragments

that were mostly broken angular pieces of foraminifera tests.

Fragments broken from the pebbles were dissolved in dilute HCl and left a slight residue which was 0.03 per cent by weight. This residue contained the following minerals given below in order of abundance. These were less than an eighth of a millimeter in diameter except a few of the pyrite grains.

Pyrite, yellow, well crystallized grains and aggregates.
Iron oxide pellets, red-brown, rounded.
Quartz, clear sub-rounded to sub-angular.
Chromite, black, sub-angular.
Leucoxene, light buff, opaque.
Perovskite, red-brown, sub-angular to sub-rounded.
Zircon, translucent sub-rounded.
Titanite, honey yellow, sub-angular.
On the filter paper was a slight stain of red-brown iron oxide and clay-like material.

Secondarily Reworked Clay

Brown Phase of Secondarily Reworked Clay.—The brown phase was a deep red-brown friable rock with an earthy appearance, quite porous and crumbled easily between the fingers when dry. It broke up readily in water and showed little plasticity when wet. This clay was spotted with light-colored calcareous patches and scattered through it were clear crystals with the form of gypsum crystals. There were also a number of white pebbles which Moore and Moore (1946, p. 209) called "water-worn pebbles of marine limestone." The pebbles and gypsum-shaped crystals are reported on separately and do not appear in the textural analysis. The same treatment was followed with this clay as the first (Tables 1, 3). The descriptions of minerals given for the Primary Red Clay apply also to this sample.

CALCITE PSEUDOMORPHS AFTER GYPSUM:—Scattered through the sample, singly and in aggregates, were crystals that had the external form of gypsum crystals. These were picked out before sieving; they varied in length from 15 to 1 mm. and from 9 to 0.6 mm. in width and made up about half of 1 per cent of the sample by weight. Each crystal was coated with a mixture of clay and calcite that would break away quite readily when the crystal was held in dilute HCl for a few moments. All of these crystals were of clear calcite, some of the larger ones were hollow geode-like structures, the calcite growing inwards from the walls; the rest were completely filled with calcite and the calcite in each was evidently part of one crystal as all of it was of the same optical orientation. The exterior of the crystals was embayed and pitted but the (110), (010), and (111) faces of the original gypsum crystal were obvious. There was no trace of $CaSO_4.2H_2O$ so it would seem that the gypsum had been dissolved and then the cavity filled with $CaCO_3$.

TABLE 3.—BROWN PHASE OF SECONDARILY REWORKED CLAY*

Size Grade in mm.	2-1	1-½	½-¼	¼-⅛	⅛-1/16	Total
Quartz	—	0.130	0.617	0.216	0.003	0.966
Zircon	0.015	0.012	0.024	0.052	0.055	0.158
Chromite	0.015	0.025	0.094	0.205	0.123	0.462
Magnetite		—	0.002	—	—	0.002
Perovskite		0.046	0.190	0.141	0.050	0.427
Leucoxene		0.027	0.046	0.080	0.060	0.213
Titanite		0.004	0.002	0.001	0.024	0.031
Muscovite				—	—	—
Garnet		—		—	—	—
Augite	0.015	0.026	0.011	—	—	0.052
Apatite					—	
Pellets	0.713	4.667	5.235	2.873	4.135	17.623
Total	0.758	4.937	6.221	3.568	4.450	

* Percentages of Minerals in Size Grades based on total weight of sample. Where a dashed line is present mineral occurs but is less than 0.001 per cent.

PHOSPHATE PEBBLES: The pebbles in the Secondarily Reworked Clay that Moore and Moore (1946) called "water worn pebbles of marine limestone" were of phosphatic material. There were seven of these, sub-angular to sub-round in shape and from 2 to 5 cm. long. Their surfaces were somewhat weathered showing a light buff colored rather porous zone to a depth of about 2 mm., the interior of each, except for one pebble, had a milky white, slightly mottled, amorphous appearance and an unctuous feel. This one pebble was dark brown and composed of rounded and sub-rounded grains in an amorphous matrix. Both the grains and

FIGURE 1

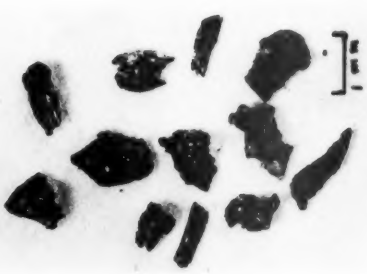

FIGURE 2

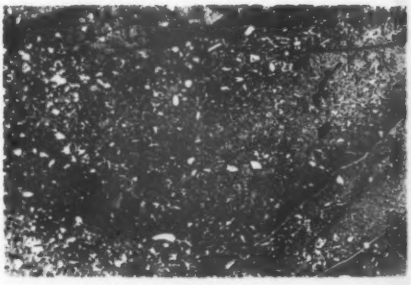

FIGURE 3

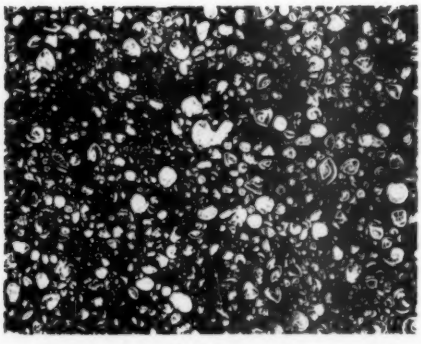

FIGURE 4

FIGURE 5

PHOTOMICROGRAPHS

greater than one-quarter mm., and group B, grains less than one-quarter mm.

GROUP A: The quartz grains generally showed some degree of rounding: of 300 particles observed, 28 per cent were angular, 41 per cent sub-angular, 22 per cent sub-rounded, 7 per cent rounded, and 2 per cent well-rounded. About a third of these grains had pitted and etched surfaces which were invariably present on the rounded and well-rounded grains as well as on most of the sub-rounded grains, but only occasionally on the sub-angular and angular grains (Pl. 1, fig. 1). However, even in the re-entrant angles of some of the angular grains, this same pitting and etching was present. Many of the larger grains were very irregular in shape, showing cavities and vug-like holes as though they came from secondary quartz, and a few had platy surfaces, possibly due to the development of imperfect cleavage.

About 90 per cent of all the grains were clear, but some were milky and others yellow-brown to red. Others were dark from dusty inclusions, and an occasional grain seemed to be made of silt stone, always well rounded. Of the clear grains, less than 10 per cent showed undulose extinction.

GROUP B: The amount of rounding was defi-

TABLE 1.—(COLUMNS 1-6) TEXTURAL ANALYSES OF BERMUDA CLAYS AND SOIL FROM PROSPECT MILITARY WELL (7)

Diameter (in mm.)	1	2	3	4	5	6	7
2–4	0.88						
1–2	0.54	0.75		0.02			7.5
1/2–1	1.38	4.90	0.55	0.08	0.07		19.3
1/4–1/2	3.08	6.31	0.60	0.10	0.17		26.6
1/8–1/4	1.76	3.60	1.56	0.33	0.49	0.11	7.7
1/16–1/8	0.75	4.62	1.96	2.38	0.46	0.13	2.8
1/32–1/16	1.0	4.6	1.6				3.2
1/64–1/32	3.5	9.8	3.1				2.4
1/128–1/64	3.0	8.6	7.1				27.2
1/256–1/128	5.5	3.2	3.8				3.1
1/512–1/256	20.4	4.1	4.3				
1/1024–1/512	31.5		7.3				
Material less than smallest size shown above	26.30	48.80	68.20	96.89	21.60	0.97	
Total	99.59	99.28	99.87	99.80	22.79	1.21	99.8
Amount soluble in HCl	13.2	31.1	6.8	74.5	77.21	98.79	99.9

Column 1 Primary Red Clay; Column 2 Brown Phase of Secondarily Reworked Clay; Column 3 Gray Phase of Secondarily Reworked Clay; Column 4 "Brick"; Column 5 "Chert" (residue after HCl); Column 6 Phosphate Pebbles (residue after HCl); Column 7 Prospect Military Well.

PLATE 2.—PHOTOMICROGRAPHS

FIGURE 1. LEUCOXENE (L), GARNET (G), CHROMITE (C), TITANITE (T)
$\frac{1}{4}$–$\frac{1}{2}$ mm. size grade.

FIGURE 2. AUGITE
Showing spiny nature of grains.

FIGURE 3. COLLOPHANITE

Thin section of "Brick" phosphate clay showing shape and distribution of collophanite grains (white). Plane transmitted light, × 10.

FIGURE 4. SANDSTONE ROCK

Foraminifera tests and fragments in dark fine-grained matrix, × 10.

FIGURE 5. AUGITE AND CALCITE IN WEATHERED IGNEOUS PEBBLE

Broken augite phenocrysts (A) and calcite patches (C) in a dark fine-grained matrix, × 15.

nitely less in this group. An eighth of a millimeter was near to the size where rounding of the grains ceased to be apparent. Some of the grains between a quarter and an eighth of a millimeter showed partial rounding, but all less than an eighth of a millimeter were angular. Of 400 grains studied, 81 per cent were angular, 17 per cent sub-angular, and 2 per cent sub-rounded. As in Group A, most of the grains (86 per cent) were clear; the rest were either milky, iron stained, or dusky.

TABLE 2.—PRIMARY RED CLAY*

Size Grade in mm.	1-½	½-¼	¼-⅛	⅛-1/16	Total
Quartz	0.180	0.180	0.140	0.130	0.630
Zircon	0.044	0.200	0.280	0.068	0.592
Chromite	0.052	0.540	0.340	0.102	1.234
Magnetite	0.012	0.030	0.022	0.061	0.125
Perovskite	0.530	0.570	0.430	0.030	1.560
Leucoxene	0.040	0.180	0.270	0.058	0.548
Titanite	—	0.030	0.051	0.012	0.093
Garnet		0.020	0.033	0.007	0.060
Augite	0.024	—	0.011	—	0.035
Epidote		—	—	—	—
Feldspar				—	—
Pellets	0.487	1.280	0.200	0.270	2.244
Total	1.369	3.030	1.757	0.738	

* Percentages of Minerals in Size Grades based on total weight of sample. Where a dashed line is present mineral occurs but is less than 0.001 per cent.

Pellets.—In the Primary Red Clay and the Brown Phase of the Secondarily Reworked Clay, it was not possible to separate certain of the grains into groups. Some of these grains were of iron oxide, others of phosphatic, and still others of calcareous material, but most of them were a mixture of all three, a mixture that seemed to range continuously between the three end members. These variations in chemical composition were reflected in variations in color, in specific gravity, and in chemical reaction that differed by such slight increments it was thought best to group them all under the term Pellets (Pl. 1, fig. 2).

However, in the Gray Phase of the Secondarily Reworked Clay, the greater part of the grains were soluble and light buff or white in color, the rest having the characteristics of the iron oxide, and are therefore given as separate groups. From those consolidated samples that were treated with dilute acid, only the iron oxide pellets are reported since they were the only members of this group unaffected by the acid.

Chromite.—The chromite grains were black and opaque, and either octahedral or fragmentary in shape; they were not attracted by the hand magnet and gave good chemical tests for chromium in borax and salt of phosphorus beads. Small splinters showed a slight transparency and $N = 2.07$.

The octahedrons usually had slightly rounded edges but some were quite euhedral; the number of octahedrons increased from 1.5 per cent of the crop in those greater than half a millimeter to 4 per cent of those between an eighth and a sixteenth of a millimeter (Pl. 2, fig. 1). The fragmentary grains were mostly rounded to sub-rounded when greater than a quarter of a millimeter and sub-rounded to angular when less.

Magnetite.—Magnetite appeared chiefly as rusty brown but occasionally as shiny black, sub-angular to sub-rounded grains. This rusty effect was evidently due to oxidation, but the grains were still very magnetic. Most of them when broken showed a black unweathered core: a few of them were rusty all the way through but still strongly attracted by the hand magnet. These rusty grains were irregular in shape and quite angular. A few of the unweathered grains showed crystal form, either the octahedron or the dodecahedron.

Zircon.—Zircon was mostly in the quarter to an eighth of a millimeter grades and made altogether nearly half of 1 per cent of the total sediment. These grains were translucent (65 per cent) to clear (35 per cent) except for a rare grain of very pale yellowish-white. Many of the translucent grains were crowded with very small irregularly oriented inclusions. Some of the larger grains were biaxial with 2V from 8°–12°; none of the grains showed crystal faces. The translucent grains were commonly sub-rounded to sub-angular while the transparent ones were sub-rounded to well-rounded; the proportion of clear grains increased in the smaller grade sizes.

Perovskite.—Perovskite is an uncommon min-

eral in most sediments but may be expected in sediments derived from melilite basalts and other basic felspathoidal rocks. Pirsson (1914) has shown that these rocks were present and were perhaps the dominant igneous rocks underlying the sedimentary cover. The perovskite grains were reddish-brown to brownish-black and always weakly birefringent, although varying in different parts of the same grain, possibly due to twinning. A partial or complete coating with a white to buff opaque layer was common (Pl. 1, fig. 3). This coating was leucoxene and there was every gradation from fresh, uncoated grains through partially coated to those that were totally covered and could only be distinguished from leucoxene grains by crushing in order to expose the perovskite core. Striations were common on the fresh surfaces, especially of the larger grains; these varied in direction in the same grain and seemed to be the external effect of the penetration twinning on the (001) and (110) faces (Dana, 1944).

Titanite.—This other allogenic titanium-bearing mineral, clear to translucent, angular to sub-rounded grains, was commonly honey-yellow but sometimes yellow-green, often with acicular but sometimes with minute irregular dust-like inclusions (Pl. 2, fig. 1). None of these grains showed a leucoxene coating or any sign of weathering or solution effect except possibly the rounding of the grain or the presence of dusty inclusions.

Leucoxene.—This ill-defined mineral, leucoxene, was found in all size grades but reached a maximum in the quarter to an eighth of a millimeter group. The grains were opaque in transmitted light and a dull white to buff, "egg shell," appearance in reflected light (Pl. 2, fig. 1). Its appearance, as noted above, as an alteration product on the perovskite grains would indicate its secondary origin. Except for rare, very minute crystals of what seemed to be brown rutile, no specific mineral could be identified in the leucoxene grains.

Augite.—The augite grains were surprisingly fresh and unaltered, and occurred chiefly as angular cleavage fragments that showed little or no rounding (Pl. 2, fig. 2). Many of them showed spiny, hacksaw terminations. These had been noted before in sediments from the Bermuda area by Larsen (Sayles, 1931, p. 440) and also by Young (1939). The grains usually appeared black, dark brown, or dark green, but in thin fragments were green to light brown. Optically they were much the same with $\alpha = 1.689$, $\beta = 1.695$, and $\gamma = 1.713$, 2V near 60°, with slight pleochroism from green to greenish-brown, maximum extinction of near 42°. There were occasional grains with maximum indices up to 1.724, these were always filled with needle-like dark inclusions which were aligned in two directions at an angle of 65°–70°, and more rarely grains with small extinction angle and optic angle that may be a type of pigeonite. Also a fibrous grain or two was present with lower indices; these may be an alteration product, possibly uralite. No purplish titaniferous variety of augite was found, which was surprising considering the amount of titanium in the source rock and Pirsson's (1914) descriptions of this mineral in the lavas. Young (1939) also reports purplish augite in the deep sea cores taken from the floor of the ocean to the east of the island.

Garnet.—An occasional grain of brown garnet was found, usually clear, isotropic, and angular to sub-angular in shape. The color varied from light to dark brown, the former have an index of refraction of 1.780 and the latter 1.870 (Pl. 2, fig. 1). Much more infrequent than the brown was the rare grain of pink to red garnet. These were angular to sub-angular, clear, and with high luster. R. I. very near 1.800.

Epidote.—Occasional, either as yellowish-green translucent, sub-angular to sub-rounded grains, or as angular, transparent light green with practically no pleochroism.

Feldspar.—Rare grains of feldspar were present, either orthoclase or acid plagioclase, usually oligoclase, and found only as particles less than an eighth of a millimeter in size. The orthoclase was fresh, with good cleavage and usually had many inclusions. The plagioclase was angular and often showed albite twinning.

Silt

The material less than a sixteenth of a millimeter was divided by decantation into a coarse and a fine fraction. In the coarse fraction the minerals were the same as in the one-eighth to one-sixteenth grade size and in about the same proportions, except that zircon was more and

quartz less plentiful. This might have been caused, at least partially, by the difference in specific gravity of the two minerals.

Clay and Colloids

The fine fraction of the Primary Red Clay, separated by decantation from the silt-sized fraction, was allowed to settle and then dried on a steam bath. The upper, finer part of this dried material was shaved off with a knife and contained the clay and colloidal phases of the sample. This fraction was studied at high magnification (× 1000, oil immersion) in oils of differing indices of refraction.

Four phases were observable in this part of the clay: a gel-like apparently amorphous matrix; scale-like to irregular shaped granules, thickly scattered through this matrix; small oolith-like bodies; and grains and fine aggregates of calcite and flakes and fibers of mica-like particles.

The matrix varied from colorless to light yellowish-brown in color, usually isotropic, but sometimes showed a faint opalescent birefringence between crossed nicols. Its index of refraction ranged from 1.580 to 1.648, the indices increasing with the depth of the color.

The granules ranged from an upper limit of about 4 microns to particles too small to be measured. They were isotropic and similar in color range to the matrix but had a higher index of refraction which ranged from 1.66 to 1.78. Generally the index of refraction increased with depth of color but not always. Some colorless granules had an index of refraction as high as the maximum obtained for any of the colored particles. No known isotropic clay minerals have been reported with a refractive index as high as those which these granules showed. Ross and Kerr (1935) found that a halloysite from Alban, Tarn, France, which was dark red from iron oxide, gave N = 1.648, the increase obviously due to this contamination. Winchell (1933) gave the indices for various alumina-silica-hydrogels, in which the index of refraction was a maximum of 1.68 where the ratio of Al_2O_3:SiO_2 was 1:0, and a minimum of 1.48 where the ratio was 0:1. The maximum he gave was close to the minimum found in these granules, and we must conclude that in all probability the high titania and phosphate content of this clay was responsible for its unusually high index of refraction. This problem is discussed in greater detail later in this paper.

Scattered through the matrix also were very small, rounded ferruginous bodies, not hard but still with definite form, in which the concentration of the iron oxide was obviously higher than in the rest of the clay; for want of a better name, these minute accretionary bodies are here called oölites (Pl. 1, fig. 4). They ranged in diameter from 3 to 20 microns and were a deeper red-brown than the rest of the clay. Most of these oölites were the same color throughout, but some showed a concentric pattern, usually with a deep red-brown center which graded rapidly into a zone or zones in which the color varied between a yellowish-brown and a reddish-brown.

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Titanite		0.004	0.002	0.001	0.024	0.031
Muscovite				—	—	—
Garnet		—		—	—	—
Augite	0.015	0.026	0.011	—	—	0.052
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the matrix of this pebble were of phosphatic material which was deeply stained with ferric oxide. The grains themselves were chiefly of fragments of shell material, mostly of foraminifera and fragments of foraminifera, and their diameters ranged from 0.8 mm. to 0.03 mm. Those pebbles which showed no shell characteristics were without any visible structure either radial or concentric. It would seem that the pebble with the foraminifera fragments was originally from an eolianite type of limestone, similar to those found in the Primary Red Clay, which had been replaced entirely by phosphatic material. All the pebbles were readily soluble in dilute HCl with some effervescence, leaving a residue of iron oxide and small mineral grains. The amount of residue varied from 3 to 8 per cent. After reducing the iron oxide present, the residue was just over 1 per cent. The sieve size grades are given in Table 1, Column 6, and the mineral content in Table 4.

Table 4.—Phosphatic Pebbles in Secondarily Reworked Clay*

Size Grade in mm.	¼-⅛	⅛-1/16
Quartz	0.010	0.019
Zircon	—	—
Chromite	0.019	0.033
Magnetite	0.001	0.001
Perovskite	0.004	0.002
Leucoxene	0.023	0.038
Titanite	—	—
Garnet	—	—
Augite		—
Gypsum	0.002	0.004
Iron Oxide	0.033	0.041
Total	.092	.097

* Percentages of Minerals in Size Grades based on total weight of sample. Where a dashed line is present mineral occurs but is less than 0.001 per cent.

Although the minerals of the pebbles are grouped together in the table, each of the pebbles was analyzed separately. The same minerals were found in each of the analyzed pebbles and in about the same proportions. The only exception was that gypsum grains were found in one of the pebbles and not in the others. These grains of gypsum were between one-eighth to one-sixteenth millimeter in diameter, clear to white in color and without inclusions. Most of them were fragments, but about a third were crystals with well defined faces. The minerals of the phosphate pebbles were similar to those found in the Primary Red Clay except for the gypsum which was present in only one of the pebbles.

Table 5.—Gray Phase of Secondarily Reworked Clay*

Size Grade in mm.	1-½	½-¼	¼-⅛	⅛-1/16	Total
Quartz	0.005	0.018	0.040	0.029	0.092
Zircon	—	—	0.003	0.005	0.008
Chromite	0.005	0.012	0.240	0.160	0.417
Magnetite	—	—	—	0.006	0.006
Perovskite	0.011	0.030	0.022	0.061	0.124
Leucoxene	—	0.024	0.120	0.063	0.207
Titanite	—	—	0.003	0.006	0.009
Garnet	—	—	0.003		0.003
Augite	—	—	—	—	—
Pyrite		—	—	—	—
Glauconite			—		—
Mica		—	—	—	—
Pellets	0.033	0.028	0.145	0.059	0.265
Calcite	0.499	0.516	0.960	1.451	3.426
Total	0.553	0.628	1.536	1.840	

* Percentages of Minerals in Size Grades based on total weight of sample. Where dashed line is present mineral occurs but is less than 0.001 per cent.

The peculiar milky unctuous phase that comprised more than ninety per cent of each of the pebbles was soluble in acid; chemical and optical tests show this to be nearly all phosphatic material, isotropic or nearly so, with N varying from 1.59 to 1.63 and was likely collophanite.

The clay material, about 1 per cent of total, was similar to that found in the clay from which the pebbles were taken.

Gray Phase of Secondarily Reworked Clay.—This clay was a light slate gray in color, in places streaked with yellowish-brown, compact, not friable and quite hard when dry. When wet the clay had a soapy feel and required more stirring to effect dispersion than any other

sample. There were a few small whitish patches of calcite aggregates scattered irregularly through it but not nearly as many as in the brown phase.

The textural analysis is given in Table 1, and mineral groupings in Table 5. Again the descriptions of the minerals given under the Primary Red Clay will apply to these with the following differences. Most of the grains of the calcareous material were of shell material, for the most part composed of complete or fragmentary foraminifera tests, a few pink prismatic grains with a "beef" like appearance, and white to buff-colored fragments from larger shells. The rest of the grains was clear to white calcite without any apparent organic structure. These grains were generally sub-rounded but ranged from well-rounded to angular.

Pyrite in small well crystallized grains and as irregular aggregates was also present, some of the foraminifera were speckled with small grains of pyrite.

Some of the silica grains were of chalcedony and there were a few tests of siliceous foraminifera. Rare irregular grains of glauconite were present as well as irregular shreds of muscovite and sub-rounded grains of apatite.

As in the previous samples, the clay portion had a matrix of colorless to light-yellow material filled with rounded oöliths of light- to dark-yellowish color, granule-like inclusions, and some clear carbonate rhombs and aggregates. Most of the matrix seemed to be a gel, isotropic or very slightly birefrigent with N = 1.595 to 1.640, colorless to brown with the higher index associated with the deeper color, and the included oöliths were also isotropic or nearly so with N = 1.72 to 1.86, and again the higher indices were in the more deeply colored portions. Present also was the lamella-like mineral found in the Primary Red Clay and called "gibbsite."

The silt-sized material was chiefly iron oxide and calcite, with occasional quartz, zircon, chromite, muscovite, and apatite grains.

"Chert" and "Brick"

These samples were evidently a modified phase of the Primary Red Clay.

"It (the Chert) occurred in masses up to about nine inches in diameter and contained practically no carbonate except minute inclusions. The brick-like material appeared to be clay which had dried to the consistency of brown porous pottery. Both occurred in much smaller quantities than the clay itself." (Moore and Moore, p. 210).

TABLE 6.—"BRICK", MODIFIED PRIMARY RED CLAY*

Size Grade in mm.	¼-¼	¼-⅛	⅛- ⅛	Total
Quartz	0.006	0.030	0.032	0.068
Zircon	—	0.008	0.030	0.038
Chromite	0.002	0.008	0.041	0.051
Magnetite	—	—		—
Perovskite	0.002	0.003	0.010	0.015
Leucoxene	0.004	0.007	0.001	0.012
Titanite	—	—	0.001	0.001
Augite	0.002	—	—	0.002
Epidote		—	—	—
Collophanite	—	0.040	0.800	0.012
Calcite	0.152	0.128	1.340	1.620
Iron Oxide	0.007	0.098	0.110	0.215
Total	0.175	0.322	2.365	

* Percentages of Minerals in Size Grades based on total weight of sample. Where dashed line is present mineral occurs but is less than 0.001 per cent.

"BRICK": This sample consisted of several irregular-shaped pieces of buff to brick-red well indurated clay rock. They had weathered surfaces which were more porous and of a deeper color than the interiors which were fine-grained and too hard to scratch with the finger nail but readily scratched by a knife. The pieces varied in color and texture from a somewhat porous buff-brown to a dense brick-red variety which was noticeably harder and heavier than the porous variety. Disintegration of this specimen was difficult but by soaking in water several days and rubbing frequently with a rubber pestle and stiff brush disintegration seemed to be complete for particles greater than a sixteenth of a millimeter but not for the clay sizes. As mentioned before, the high phosphate content of this clay made it appear inadvisable to attempt to separate the smaller sized particles.

Table 6 gives mineral content in the size grades and Table 1, Column 4, the textural analysis in sizes greater than the one-sixteenth

millimeter. Again the mineral suite was much the same as in the Primary Red Clay. The quartz was nearly all angular and clear, mostly less than a fourth of a millimeter in size. Some of the grains were pitted and iron-stained, and in the one-eighth to one-sixteenth millimeter grade about a third of the grains were speckled on their surface with pyrite.

TABLE 7.—"CHERT", MODIFIED PRIMARY RED CLAY*

Size Grade in mm.	1-½	½-¼	¼-⅛	⅛-1/16	Total
Quartz	—		0.002	0.005	0.007
Zircon	—	0.003	0.005		0.008
Chromite	—	0.022	0.036	0.052	0.110
Magnetite	0.003		0.005	0.005	0.013
Perovskite		0.009	0.008	0.013	0.030
Leucoxene	0.003	0.018	0.025	0.004	0.050
Titanite	—		0.003		0.003
Augite	0.003	—	—		0.003
Garnet				—	—
Feldspar				—	—
Iron Oxide	0.056	0.115	0.379	0.366	0.916
Total	0.065	0.167	0.463	0.445	

* Percentages of Minerals in Size Grades after treatment with dilute HCl based on total weight of sample. Where a dashed line is present mineral occurs but is less than 0.001 per cent.

One mineral, collophanite, not found in the previous clays was abundant in the "Brick" although it did not show up in the mineral crop which had been treated with acid. It occurred as opaline to white, smooth, sub-angular to rounded grains (Pl. 2, fig. 3) all less than a quarter of a millimeter in diameter. They were not oölitic nor did they show any radial structure but appeared to be amorphous and structureless. The thin sections showed some of the collophanite grains to be scattered rather evenly through the rock but most of them concentrated in irregular patches and in uneven sub-parallel bands. Since most of the harder minerals appeared to have been rubbed out of the thin section, a slice was cut and polished and then etched for a few seconds in dilute HCl, after which it was gently washed with hot water. Here the partly dissolved collophanite was apparent and also the insoluble minerals. These, the quartz, chromite, and so forth, were also partly scattered through the slice and partly concentrated in the patches and bands with the phosphate mineral. These bands varied in width up to 3 mm. and were from 8 to 20 mm. apart, with the collophanite and coarser insoluble minerals making up nearly 50 per cent of the area of the bands. The patches were irregular in shape, from a half to 5 millimeters across, with about the same distribution of minerals as in the bands, the matrix between these grains was of very fine-grained brown material.

The fine fraction of this sample seemed to be mostly collophanite with some calcite, and over 80 per cent was soluble in acid. The residue was amorphous material very much like in the Primary Red Clay, consisting of a brownish matrix with N = 1. 620 to 1.640 crowded with granules whose index of refraction varied from 1.640 to 1.760 and many oölith-like bodies of iron oxides with indices ranging from 1.705 to 1.755.

"CHERT": This specimen consisted of irregular fragments up to 7 cm. across; each showed a porous surface weathering that was a lighter brown than the interior, a reddish-brown, dense, almost flint-like substance. They were similar to the "Brick," only harder and did not disintegrate in water but did break up in dilute HCl with slight effervescence. The minerals reported in the grade sizes were those not soluble in the acid. Most of the dissolved material was collophanite. (Table 1, Column 5).

The minerals found were similar to those in the Brick and were chiefly in the grades less than a quarter of a millimeter (Table 7), with iron oxide, leucoxene, and chromite the common minerals. The quartz in both the Brick and Chert specimens was definitely less in amount than in the other samples.

A thin section showed very much the same appearance as the section of brick-like sample but it was deeper brown, there were fewer collophanite grains, and these were rather evenly distributed through the slide. There were also irregular patches of white calcite which showed clear crystals that had either filled cavities or had grown in the rock.

Most of the material less than a sixteenth of a millimeter was fine-grained collophanite (N = 1.638), but there was also some of the in-

soluble amorphous gel-like brown matrix with oöliths and granule-like inclusions.

It was apparent that the "Brick" and "Chert" phases owed their peculiar features to the large amount of phosphatic material in them, which seemed to act as a binding agent to indurate the clay. Whether these pebbles were formed in the clay or were brought in from elsewhere is not wholly apparent. Their angular shape and slightly weathered surfaces suggest an allogenic origin, but this might have been the result of changes in the clay after their formation.

Marine Limestones

Introduction.—A series of marine limestones were found above the clays. These are given below in the same sequence that Moore and Moore listed them, ranging from the oldest, the Cladocora rock, to the youngest, the Brachydontes rock.

Cladocora rock.—This sample consisted of large pieces of broken and unbroken fossil material well cemented in a very fine-grained calcereous matrix that might be called a calcilutyte and the rock called Biostromal limestone (Pettijohn, 1949, p. 299). The coral *Cladocora arbuscula* was the characteristic fossil and it was usually unbroken (Moore and Moore, p. 210). The rock contained many cavities, but where cemented it was hard and the samples bore out Moore's observation that this was formed *in situ* in fairly deep water below the zone of wave action.

The matrix varied in color. In some samples it was chalk white; in others a light-gray. About 150 grams of each type was dissolved in dilute HCl; the white gave an insoluble residue of 0.16 per cent, the gray 0.36 per cent. In both types, all of the insoluble grains were less than 0.061 mm. and consisted of more than 90 per cent of brassy, well-crystallized pyrite. The rest of the residues were as follows: quartz in sub-angular grains and in small euhedral crystals and as rod-like fragments, opal in clear to colorless almost spherical grains and rare grains of colorless well-founded zircon. A small piece of each type dissolved in acetic acid gave also a few collophanite grains.

Oculina rock.—The Oculina rock was very similar in appearance to the Cladocora rock described above. The rock consisted of coarse, broken and unbroken, fossil fragments and contained many cavities, but where the fine-grained calcite cement was present the rock was very hard. The residue after dissolving in dilute HCl was 0.64 per cent. Over 85 per cent of this residue passed through the one-sixteenth millimeter sieve. The material on the sieve was nearly all black rounded grains of carbonaceous material with a few grains each of angular quartz and pyrite and two grains each of garnet and perovskite. That which came through the sieve was nearly all a powder of iron oxide and clay-like material intermixed with dark-gray carbonaceous particles, as well as a few grains of crystalline pyrite in separate crystals and in aggregates, quartz angular and clear, chalcedony rounded, and rare grains of andesine feldspar, zircon, and apatite.

Undated old rock.—Large broken fragments of fossils, chiefly pelecypod shell material and broken clusters of branching corals cemented by light buff to gray calcareous matrix made up chiefly of calcite mud and small shell particles which were mostly fragments of foraminifera. The residue of 0.04 per cent after HCl was all very fine-grained pyrite.

Sandstone.—A white to light-gray limestone rock with many cavities, some of them up to 8 cm. across. This rock had a sandy appearance, in thin section these grains were seen to be small fragments of shell, mostly foraminifera (Pl. 2, fig. 4) in a calcareous mud too fine-grained to be resolved by the microscope. Scattered through this matrix were pieces of shell, the largest of which were weak pelecypod shell fragments. These are angular and up to 15 cm. long.

The insoluble residue after dilute HCl was 0.054 per cent, most of it less than a sixteenth of a millimeter but a little up to a quarter of a millimeter. This material was chiefly black carbonaceous particles with an occasional grain of angular clear quartz, aggregates and crystals of pyrite and a rare grain of zircon, and leucoxene, and a little brown clay-like substance with N = 1.570.

Shell conglomerate rock.—The sample consisted of two irregularly shaped but somewhat rounded pebbles of a gray compact limestone. Broken fragments of shell, mostly those of

pelecypods, in a very fine-textured, gray matrix, were roughly aligned in sub-parallel fashion. Close examination showed that the shells had been perforated by some boring animal and these holes later filled with well-crystallized calcite. In thin section the bore holes appeared as cylindrical aggregates of clear calcite about 0.02 mm. in diameter and up to 3 mm. long. Faecal pellets were also common. These were ovaloid in shape and darker than the rest of the rock.

The insoluble residue (1.02 per cent) seemed to be all pyrite, ranging from well-formed crystals 0.025 mm. in diameter to dust-like particles. The color of the rock and of the pellets was due to the finely divided pyrite. There was a concentration of these particles in the faecal pellets and also where the matrix joined the fossil fragments.

Mangrove peat.—A soft, porous, friable peat-like rock of light-gray color streaked with black. Effervescence was very rapid in dilute HCl leaving an insoluble residue of 32.8 per cent. This residue was mostly, altered, easily crumbled, plant material and some clay. There were a few six-sided, roughly barrel-shaped grains with rounded edges which were harder than the other organic material. They were from a half to an eighth of a millimeter in diameter. Besides these, there were some rounded and spicule-shaped grains of chalcedony and less frequently angular quartz and sub-rounded zircon particles. The soluble phase of the rock was calcareous, composed of aggregates and single lath-shaped and also rhomb-shaped crystals of calcite along with shell fragments and broken foraminifera tests. These were scattered through the plant material and were also in thin irregular streaks and patches.

Lampanella clay.—A light-buff limestone composed of coarse angular fragments of shell chiefly of the gastropod *Lampanella minima* (Moore and Moore, 1946), with a sandy calcareous matrix. There were many irregular cavities as if the cementing material had been washed in but had not filled all the openings between the shell fragments. The insoluble residue was 1.02 per cent by weight and nearly all a light-brown clay with N = 1.633. An occasional grain of angular quartz, apatite, as well as flakes of muscovite and a few dust-like particles of pyrite were present.

Brachydontes rock.—The same general description can be given to this rock as to the Lampanella clay. The only difference seemed to be that the shell fragments were mostly of the littoral mussel *Brachydontes exustus* (Moore and Moore, 1946). Insoluble residue 0.85 per cent by weight carried the same minerals as in the Lampanella clay.

Material from Bore Hole

Some of the material of the weathered zone above the basalts was sent to the writer by Professor Adolph Knopf of Yale at the request of Mr. H. C. Stetson. These samples were all small and no more than about 3 grams could be used from any one sample. It is improbable that such small samples would give more than a rough approximation of the true distribution of the minerals, so only a comparative expression of their frequency is allowable even though the samples themselves were carefully studied. Table 8 gives the minerals greater than a sixteenth of a millimeter present in the samples of the weathered volcanics below the limestone rock. Although there were some samples of the soft white Bermuda lime rock which occur above the weathered volcanics, the residue from such small amounts was very slight, usually no more than a slight stain on the filter paper, so no report is made on the limestones of the Bore Hole.

For the weathered volcanics the samples were treated with dilute HCl and as in the clays the residue was treated with dilute acid and stannous chloride to clean the coating of iron oxide from the grains. The material was then sieved and the heavy and light minerals separated. Because this hole was made with a spud drill, the sieve sizes are not reported although it was obvious from the partial rounding of some of the grains they had not been affected by the drill.

In each sample more than 90 per cent of the insoluble residue was a weathered, glassy or hypocrystalline sometimes porphyritic material, light brown and often filled with minute black inclusions. These inclusions were likely mag-

netite since those grains with many inclusions were readily attracted to the hand magnet. It was possible to identify some of the phenocrysts in the hypocrystalline phase, but the matrix colorless needle-like inclusions that seemed to be apatite.

Besides these minerals there were separate grains of the following in order of decreasing frequency;

TABLE 8.—SUMMARY OF MINERALS FROM THE GIBBS' HILL BORE HOLE, BERMUDA

Pirsson's number	Depth below surface in feet	Pirsson's Description	Quartz	Zircon	Muscovite	Biotite	Feldspar	Augite	Garnet	Chromite	Magnetite	Perovskite	Zeolite	Melilite	Nephelite	Serpentine	Chalcedony	Iron Oxide Pellets	Pyrite	Barite	Leucoxene	Volcanic Glass and unidentified hypocrystalline material
14	518	Brown earthy fragments	T		O	T	O			O	C	O	T			T		C		C	O	VA
16–17	550–573	Brown, earthy, with small gray fragments	O	O	O		O			C	C				T	T		C		C		VA
18–19	573–578	Soft blackish gray fragments filled with calcite balls	O	O	T	T	T			C	C			O				C	C	C	O	VA
20	578–583	Brown earthy fragments, filled with small calcite balls	O	O			T	C	T	C	C				O			C	C	O		VA
23	665–695	Fragments of a very dense lead-gray lava, soft and brown in places on the surface	O	O				C			C		O				O					VA
24	695–708	Lead-gray dense lava, some brownish, amygdaloidal		T			O	T			C		T		T							VA

The samples were so small that the frequency of the minerals can only have comparative significance; thus, T—trace, O—occasional, C—common will not be defined within any given limits. VA—very abundant, in each case this is 90 per cent or more of insoluble residue of sample.

was a confused aggregate of weathered products of a felty ground mass. Along with the weathered volcanic material, but not in it, were other minerals. These were not included in a matrix and for that reason are called here "separate minerals" (Table 8).

SAMPLE 14—518–544 feet below surface. "Brown, earthy fragments," Pirsson. 1.12 grams gave a residue of 26 per cent by weight. The dissolved material was chiefly calcite with some iron oxide. The volcanic material which constituted nearly all the insoluble residue was in sub-angular to sub-rounded grains, the glass of which was light brown, isotropic with N-1.530 to 1.538. Crushed grains of the hypocrystalline material showed fragments of nephelite, oligoclase, mica, both biotite and muscovite, analcite, and serpentine. There were also some all of these grains and the volcanic material went through the half-millimeter sieve.

Barite—as angular to sub-angular clear to translucent grains.

Iron oxide—in irregular, sub-rounded, brown earthy pellets; some were magnetic and these had either a magnetite core or small black magnetic particles scattered through them.

Magnetite—black to rusty brown, sub-angular, a few were octahedrons.

Leucoxene—opaque, sub-rounded, buff colored, some when crushed showed very small brownish crystals with high birefringence with N above 2.40. These may be anatase.

Chromite—black angular to sub-angular, a few octahedrons.

Perovskite—lustrous red-brown translucent, slightly birefringent.

Feldspar—angular, clear, fragments of oligoclase.

Quartz—clear, angular, grains all less than one-eighth millimeter in diameter.

SAMPLE 16–17—from 554 to 573 feet below surface. "Brown, earthy, with soft gray fragments," Pirsson. 3.23 grams gave insoluble residue of 35.5 per cent by weight all of which passed through the half-millimeter sieve, over 90 per cent was glassy to hypocrystalline material, the rest separate grains. The glass had $N = 1.553$ to 1.559, black magnetic inclusions were common in the glass and in some grains were so frequent that the grains appeared in the heavy mineral crop. Nephelite, oligoclase, and a sericite-like mica with some serpentine were present in the hypocrystalline grains.

Separate grains of: magnetite, barite, iron oxide, chromite, leucoxene, having the same characteristics as in Sample 14. Quartz, angular to sub-round, mostly clear but some with needle-like inclusions of what appeared to be apatite. Zircon in clear, sub-angular to sub-round grains.

SAMPLE 18–19—573–578 feet below surface. "Soft blackish gray fragments, filled with small calcite balls, and brown earth fragments," Pirsson. 2.51 grams gave insoluble residue of 45 per cent, again nearly all weathered glass or hypocrystalline material and all passed through the half-millimeter sieve. The glassy phase had $N = 1.530$ to 1.542 with many magnetite inclusions. Biotite in fragments up to 0.12 mm. was commonest mineral of the hypocrystalline grains. Also present were nephelite, and a mineral with anomalous extinction and abnormal birefringence with N near 1.630. This was thought to be melilite.

Separate grains in order of frequency: Pyrite in aggregates of brassy crystals, barite, magnetite, chromite, iron oxide, zircon and quartz, with same characteristics as before.

SAMPLE 20—578–583 feet below surface. "Brown earthy fragments filled with small calcite balls," Pirsson. 2.02 grams gave insoluble residue of 19.6 per cent by weight. All passed through the 1-mm. sieve. Weathered volcanic material as before with N of glass 1.530 but some darker brown $N = 1.542$.

Minerals in hypocrystalline grains: biotite, nephelite, albite, serpentine, melilite, and analcite, and a fibrous mineral of low birefringence, N near 1.520 that may be a zeolite, possibly thomsonite.

Separate grains of: pyrite, magnetite, iron oxide, augite, chromite, oligoclase, quartz, zircon, and garnet in order of frequency. These grains were the same as in previous samples except that some of the grains that might otherwise be called zircon were translucent instead of clear and broke rather readily into rectangular pieces. Their birefringence was low and N was variable from 1.830 to 1.875—these may be malacon, an altered zircon (Winchell, 1933, p. 184).

The largest grains in the sample were angular cleavage fragments of green-brown augite slightly pleochroic with $\alpha = 1.700$, $\beta = 1.705$, $\gamma = 1.720$, 2V near 60°. These show no signs of weathering and were apparently broken fragments of larger crystals. A few grains of brown angular isotropic garnet were also present.

SAMPLE 23—665–695 feet below the surface. "Fragments of a very dense lead-gray lava, soft and brown in places on the surface," Pirsson. This sample was from the lower part of what Pirsson described in his geologic section as "Sands and gravel composed of rounded waterworn volcanic debris, unoxidized and gray to black in color." The fragments were a mixture of broken and of partially rounded, slightly weathered, volcanic material and a few separate mineral grains. Nearly all the volcanic particles were a glass with $N = 1.535$, filled with minute magnetite inclusions; a few were microporphyritic with small phenocrysts of augite in a groundmass of glass, magnetite, augite, analcite, and possibly some melilite.

Separate grains: fresh angular green-brown augite; rounded irregular grains of chalcedony; colorless to very light pink zircon grains, usually angular fragments but a few showing bipyramids; a few angular grains of clear quartz. All of the separate grains passed through a quarter-millimeter sieve.

SAMPLE 24—695–708 feet below the surface. "Lead-gray dense lava, some brownish; amygdaloidal," Pirsson. This was just below the altered volcanics and sand in the amygdaloidal upper phase of the first basaltic lava flow. There was 15 per cent by weight of calcite present as separate grains and aggregates and as grains and aggregates attached to the igneous rock. The individual calcite grains ranged up to 1.5 mm. in length and were mostly angular cleavage fragments, although there were a few sub-angular grains. Also as separate grains was an occasional angular clear grain of quartz.

About a third of the volcanic material was a brown isotropic glass, part of which contained few black inclusions, $N = 1.463$. The rest was filled with minute magnetite inclusions. The glass in this had $N = 1.490$ to 1.505. The other two-thirds was felsophyric with brownish-green augite phenocrysts in a fine grained groundmass, in which nephelite, orthoclase, analcite, and some inclusions of apatite were identified. The optical properties of the augite were as follows:

$\alpha = 1.691$, $\beta = 1.698$, $\gamma = 1.717$

$2V = 63° \pm 2°$

x—yellowish green, y—greenish brown, z—greenish brown.

No samples of the lower lavas were sent to the writer.

Water-Worn Pebbles

An unusual rock was found by William Livingston at a depth of 27 feet in the dredged material at Town Cut Channel St. Georges Harbour and was from the Hard Bermuda limestone. This was the oldest eolian limestone found in Bermuda (Livingston, 1944) and seemed to be the equivalent of the Walsingham eolianite of Sayles (1931). This specimen was an angular fragment of light-buff, highly fossilferous limestone in which were a number of well rounded pebbles. These pebbles were of two kinds, white carbonate pebbles up to 2 cm. in diameter and dark-gray, almost black, well rounded pebbles that appeared to be a water-worn tuff. One of these dark pebbles was much larger than the others. It was roughly elliptical in shape and measured 4.7 cm. by 3.5 cm. by 3.2 on the three axes. The other dark pebbles were much smaller, all less than 1.5 cm. long diameter. Fragments of the large dark pebble in dilute HCl effervesced freely and gave a residue of 6.4 per cent by weight. This residue consisted of porous, easily broken, irregular, weathered volcanic fragments, augite phenocrysts and cleavage pieces, and a few small grains of clear, angular to sub-angular quartz. The weathered volcanic material had some small clear laths of andesine and a few grains of nephelite, a little of a yellowish mineral that seemed to have the optical properties of melilite as well as a few pieces of glass, $N = 1.560$, but nearly all of it was a confused aggregate of weathering products through which were scattered innumerable small, irregular, dark inclusions.

The greater part of the dark pebble was calcite. This was apparent from the acid treatment and also from the thin sections. Most of the calcite was in very small to sub-microscopic grains interspersed with the dark volcanic material, but there were stringers, patches, and spots of clear crystalline calcite that were irregularly dispersed through the rock. The smaller dark pebbles were of the same material as the large one described above.

Thin sections and the slices from the large dark pebble showed several very dark angular patches of a weathered augite basalt porphyry. These patches, the largest having an area of about 1.5 square cm., were irregularly scattered throughout the pebble, and all of the identifiable igneous minerals were in these. Augite was the only common igneous mineral. It occurred as phenocrysts and fragments of phenocrysts up to 2.2 mm. long and 1.8 mm. wide scattered through the basaltic patches (Pl. 2, fig. 5). The broken grains often showed hacksaw terminations, but the only other evidence of weathering was a slight peripheral zone darker than the interior and well developed cleavage lines in some of the phenocrysts. Optical data on the unaltered interiors gave, $\alpha = 1.706$, $\beta = 1.711$ $\gamma = 1.725$, 2V near 60°, maximum extinction angle of 35° and a very slight pleochroism in shades of greenish-brown. The gray matrix which enclosed the darker angular basaltic fragments was mostly fine-grained calcite filled with small dark inclusions through which were squarish patches up to half a centimeter in size with few if any inclusions and consequently light gray to white in color. This matrix might have originally been an andesitic tuff now altered to and also impregnated with calcite, the light patches the relics of feldspar phenocrysts.

These pebbles of altered tuff were evidently rounded rapidly and then quickly enclosed in the limestone because in places at the edge of the pebble broken augite phenocrysts were quite fresh at the junction with the limestone, but the border of the crystal inside the pebble showed a zone of alteration.

As mentioned above, there were also some white rounded pebbles from 1 to 2 cm. in diameter in the limestone. These were all aragonite, and consisted of fine interlocking acicular crystals that gave the pebbles a compact sub-vitreous appearance, very similar to a white jade.

The conditions that formed this rock appear to have been as follows: volcanic eruptions of explosive type, both andesitic and basaltic, gave rise to the tuff. This was then altered, chiefly to carbonates, possibly with calcite being deposited at the same time. The calcareous tuff was then broken up either subaerially or by wave action and the pebbles were quickly rounded and carried into the area where the

Hard Bermuda limestone was being deposited. It was more difficult to account for the aragonite pebbles, but they may have been formed as the result of hot waters coming through the basalt tuff (Milner, 1940) and then broken out of the tuff and carried along with the dark pebble into the area of limestone deposition.

Prospect Military Well Sample

This sample was from a depth of 123 feet below the surface of the Military Well at Prospect and was Earth layer number IV of Livingston (1944). This well, whose top was 197 feet above sea level, was excavated by the Royal Engineers in 1867 to a depth of 190 feet. It was deepened to 196 feet in 1899, and cleaned out in 1938 when the samples described by Livingston were taken. This Earth layer IV is 12 inches thick and would seem to be the same rock as the Signal Hill eolianite of Sayles (1931), who described it as "a rock of accretion, although in local pockets the products of residual decay have accumulated."

The sample analyzed was uncompacted material, brown to buff in color and made up of broken fossil material which when sieved gave the following (Table 1, Column 7). Particles greater than half a millimeter were composed of aggregates, chiefly from the one-eighth to one-quarter millimeter grades so they should be added to that size group, while the less than one-sixteenth millimeter material was fine comminuted particles mostly in the fine silt sizes. The larger grains were fossil fragments, angular to sub-angular in shape, white to red-dark brown in color depending on the amount of iron stain present.

A residue of 0.011 per cent by weight was left after dissolving the calcite in dilute HCl and the following minerals were present, given in order of their abundance:

iron oxide, in brown irregularly shaped particles
quartz, angular to sub-angular, clear grains
pyrite, in separate grains and crystalline aggregates
carbonaceous material, black irregular grains
perovskite, red brown sub-angular with small striations common on their surfaces
chalcedony, angular, white to buff in color
augite, spiny fragments, green, unaltered, with N of beta near 1.720
zircon, rare, colorless angular
titanite, rare, honey yellow color, sub-angular

Of the above minerals, all but a few were between one-quarter and one-sixteenth millimeter in diameter. The calcite portion of the sample was grouped about two maxima, one the broken fossil material near the quarter-millimeter size and the other the comminuted particles, in the fine silt size. Livingston (1944) considered that these "fossil earths" were formed when the area was well above sea level and there was no large movement of sand but a drifting of small quantities over a long interval of time for the formation of each earth layer. He further noted that in hollows or in valleys these fossil earths were thick and dark brown, but higher up the hill slopes they were thin and lighter in color. Very much the same description was given by Sayles, who cited three processes that are responsible for their formation: first, the insoluble residue of large amounts of dissolved eolianite, which were deep red or chocolate-brown; second, fine calcareous sediment blown about might be added to the insoluble residue and where this was important the soils were light-colored pink to gray to cream color and high in carbonate; third, concentration by rain wash from the slopes of the material of the other two processes. This last gave soils that were very variable in thickness and deeper in color than by the other two processes.

It would seem then that the soil analyzed above belongs to the second process that Sayles stipulated in soil formation. His table on the petrology of the eolianites and soils lists six samples of Signal Hill soils. Their insoluble residues are given for material coarser than silt; for five of them, their insoluble residues were 0.001 per cent and the other 0.005 per cent. The amount coarser than silt in the above analyzed sample is 0.006 per cent which is close to his highest figure. The minerals are much the same except no pyrite, iron oxide, or carbonaceous material was listed in his Table.

If these three minerals which make up about half of the sample are disregarded, then the amount of insoluble residue falls well within the percentages which Sayles gives for the Signal Hill soils.

Phosphate and Titania

The phosphatic pebbles and the collophanite in the so-called Chert and Brick suggested that tests for phosphorus should also be made on other specimens. At the same time it seemed advisable to make tests for titanium on the fine fraction of the clays and also on the limestones. Table 9 gives the results of these tests. For each clay, 10 grams of the clay-sized material was quartered down to about 1 gram. From each limestone sample small pieces were broken to make about 10 grams and crushed to pass a 100 mesh sieve, then quartered down to about a gram. Three portions of 0.25 grams each were accurately weighed from each sample. Two of these portions were used in the test for phosphorus, one as a check against the other and a third portion for the titanium test.

Table 9.—Tests for Phosphorus and Titanium

	Phosphorus Test	Titanium Test
Primary Red Clay	vs	s
Brown Phase of Secondarily Reworked Clay	s	m
Gray Phase of Secondarily Reworked Clay	m	s
Brick	s	tr
Chert	vs	tr
Phosphatic pebbles (called marine limestone pebbles by Moore)	vs	m
Cladocora rock	m	tr
Oculina rock	tr	mtr
Undated old rock	m	tr
Sandstone	tr	mtr
Lampanella clay	tr	mtr
Brachydontes rock	tr	tr
Water-worn pebble in Bermuda Limestone	m	tr
Bermuda limestone	m	tr

vs (very strong) between 42.3 and 8.5% P_2O_5 and 100–20% TiO_2; s (strong) between 8.5 and 1.7% P_2O_5 and 20–4% TiO_2; m (medium) between 1.7 and 0.34% P_2O_5 and 4–0.8% TiO_2; tr (trace) between 0.34–0.07% P_2O_5 and 0.8–0.16% TiO_2; mtr (minute trace) less than 0.07% P_2O_5 and less than 0.16% TiO_2.

The samples used in the phosphorus tests were each taken up in 10 cubic cm. of 6 normal nitric acid, dried out on a steam bath, and 10 cubic cm. more of 6 normal nitric acid added. This was filtered, washed, and the filtrate evaporated down to about 15 cubic cm. A fresh solution of ammonium molybdate was added in excess and if necessary water added to make 25 cubic cm. of solution. The amount of yellow precipitate of ammonium phosphomolybdate was compared to solutions containing a known amount of fluoro-apatite which had been treated in a manner similar to the samples. These comparison solutions contained 0.25, 0.05, 0.01, 0.002, 0.004 grams of apatite, respectively, in each 25 cubic cm. of solution.

A like procedure was followed in the test for titanium in the rutile, using the hydrogen peroxide test after Brush and Penfield (1926, p. 128). Again comparison solutions were made, this time containing rutile with similar amounts in solution to the apatite series (Table 9).

Discussion

Introduction

The following discussion is based on the assumption that the Primary Red Clay, which underlies the marine limestones in the Castle Harbour and Ferry Reach areas and from which the other clay rocks have been derived, was not a local pocket of accumulation but of considerable extent. Moore and Moore (1946) pointed out that because this clay did not make good fill no large amounts of it were dredged up, yet it was considered to be abundant. It was also found by the dredgers at about the same depth, 40 feet, in considerable area inside the northern reefs. No other rock was found below it, although the dredges were often working to a depth of 50 feet. If this had been a clay of accumulation formed on the floor of a sink or cave, it is hardly likely that they would not have struck the floor at some place. Also the absence of any of the land snail shells that Sayles (1931) found in all of the interglacial soils and the presence of foraminifera and sponge spicules (Moore and Moore, 1946) indicate a different history for this clay from that of the soils.

As noted in the description of the Primary Red Clay, fragments of white angular eolian limestone were found by the author in the

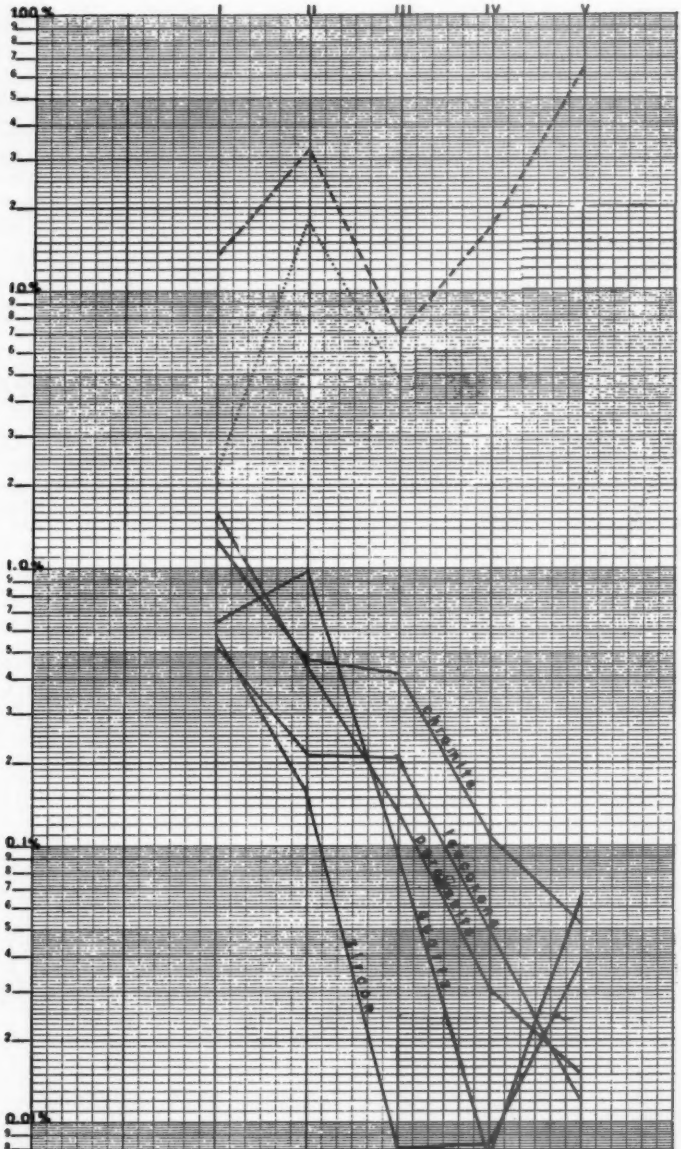

FIGURE 1.—SEMI-LOGARITHMIC DIAGRAM SHOWING SIZE DISTRIBUTION OF MINERALS GREATER THAN ONE-SIXTEENTH MILLIMETER AND PERCENTAGE WEIGHT OF MINERALS SOLUBLE IN DILUTE HYDROCHLORIC ACID IN THE BERMUDA CLAYS

I = Primary Red Clay; II = Brown Phase of Secondarily Reworked Clay; III = Gray Phase of Secondarily Reworked Clay; IV = "Brick"; V = "Chert"; Dashed line = material soluble in dilute hydrochloric acid; Dotted line = percentage weight of pellets.

sample sent to him. These pebbles were not mentioned by Moore so they are probably not plentiful. They may or may not have come from any of the known surface eolianites. Pirsson and Vaughan (1913) described all the 360 feet of limestone above the weathered volcanoes as "limestone of the usual character known in Bermuda," and since the surface eolianites and soils range in age through Kansan Glacial age to the present and probably include even the Aftonian interglacial and the Nebraskan glacial ages in the lower part of the Walsingham (Sayles, 1931), it seems unlikely that the more than 200 feet of limestone below these surface rocks and above the weathered volcanics could belong to one Glacial age, Nebraskan, even if all of the Walsingham was younger than the Nebraskan, for then the sediments of the Nebraskan would be thicker than the formations of all the other Pleistocene ages put together. Also the amount of insoluble residue in these pebbles (0.03%) was considerably more than Sayles found in the surface eolianites, where the range was from 0.002 to 0.004%. These eolianites, older than those studied by Sayles, may be all Prepleistocene in age, formed when a much greater amount of materials from the underlying volcanics was being deposited with the carbonates.

Sayles correlated the soils in the surface formations with the interglacial stages from the Yarmouth to the present. He was not sure whether the Aftonian interglacial stage was represented by part of the Walsingham eolianite or not but thinks that it might have been. Present-day estimates put the length of the Aftonian interglacial age at about 200,000 years and the Yarmouth age at about 300,000 years (Flint, 1947). Sayles found the average thickness of the Shore Hills, the thickest of the soils in the eolianites, was 4 feet. In some pockets it reached 12 feet; this evidently represented the greater part of Yarmouth time. It would be expected that, if the Primary Red Clay represented the Aftonian, it would not be as thick as the Shore Hills soil, and yet it seems to have a considerably greater thickness over an area much greater than any pockets of accumulation. It is well, however, to examine in some detail the results of the above analyses and graphs before proceeding further.

Diagrams and Graphs

A variation diagram (Fig. 1) shows the total percentages in the sieve sizes for the five most persistent minerals in each of the clays. These minerals are all allogenic except perhaps leucoxene, which may have, in part at least, formed in the sediment after it was deposited.

A short explanation of the graphs (Figs. 1–6) may make them easier to understand. A logarithmic scale was used because the small values can be expanded and the larger ones compressed so that the great variation in amount of the different minerals in these sediments could be readily shown. Also, the rate of change as indicated by the slope of the line could be readily seen and this is usually a much more important factor in the study of sediments than the percentage change which an arithmetical graph would show. The vertical scale shows cycles that vary by a factor of x10, thus the same vertical distance is given for a change from 0.001 per cent to 0.01 per cent as is given for one from 1 per cent to 10 per cent. Although these are shown as semi-logarithmic scales, those showing the size grades (Figs. 2–6) are actually double logarithmic scales because the phi values of the sediments are plotted on the abscissae and this is also a logarithmic function commonly employed today in which $\phi = -\log_2 E$ where E is the diameter of the grains in millimeters (Krumbein, 1936).

Interpretation of Graphs and Tables

Explanation.—That these were grab samples, chosen haphazardly as circumstances permitted, must be kept in mind when interpreting the analyses. Rapid variation both laterally and vertically in the amount and particle size of these minerals seems likely from the very nature of these sediments and only obvious trends will be mentioned. The rather detailed analyses were made because these were the only sediments that so far have been found between the surface eolianites and the underlying weathered volcanics.

Figure 1.—Although the Primary Red Clay seemed to have been the rock from which the other clays were derived, there is no evidence

that the Brick or Chert had passed through several successive stages to reach their present composition, that is, were at one time the Brown Phase, then the Gray Phase of the Secondarily Reworked Clay, and then later developed into their present form. Nor is it likely that the Brown Phase was at one time an intermediate stage of the Gray Phase. On this diagram are plotted three different types of values, the unbroken lines connect points that indicate the per cent of each of the five most persistent minerals in the five clays, the dashed line the amount of material soluble in hydrochloric acid in the same five samples, and the dotted line the amount of phosphatic-calcareous-iron oxide pellets greater than one-sixteenth millimeter in the first three samples. This last could not be given for the Chert and Brick since disaggregation for these was not attained until the binding material had been dissolved. In the first three samples the soluble material was mostly phosphate and calcium carbonate; in the last two, the Brick and Chert, it was mostly phosphate, which accounted for the failure in disaggregating the particles until this phosphate had been dissolved. A large part of the soluble material was in the sieve sizes, especially in the reworked clays.

The minerals from the samples were plotted in this graph so as to maintain the most consistent trend between the sample with the largest amount of the minerals and that with the smallest amount. When this was done, the position of the different samples in the graph followed the same order that Moore and Moore, (1946) reported them.

The slopes of the lines were all downward with three exceptions: the quartz line from the Primary Red Clay to the Brown Phase of the Secondarily Reworked Clay and the quartz and zircon lines from the Chert to the Brick. These upward slopes show that these minerals increased in amount in the sample to the right while in all other cases the slopes of the lines are downward, thus indicating decreased amounts.

The lines of the graph fall naturally into three pairs, the quartz and zircon, except for the rise of the quartz in the Brown Phase of the Reworked Clay, have the same general trend; those of the perovskite and titanite,

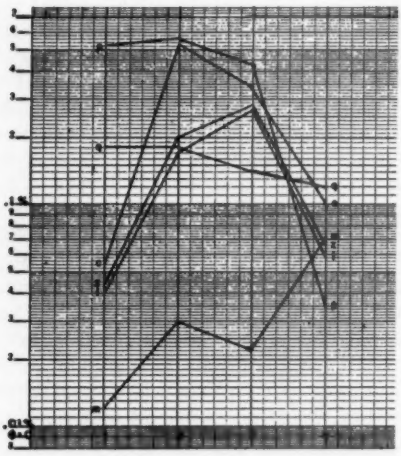

FIGURE 2. MINERAL DISTRIBUTION IN PRIMARY RED CLAY

q = quartz; c = chromite; p = perovskite; m = magnetite; z = zircon; l = leucoxene.

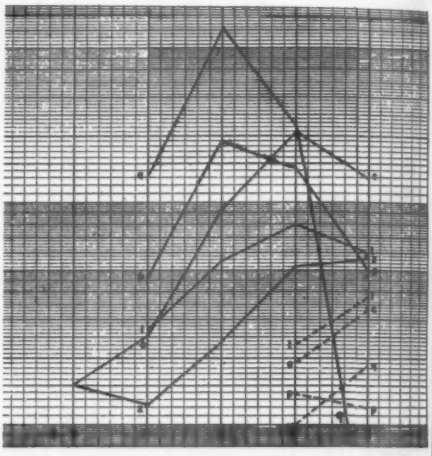

FIG. 3. MINERAL DISTRIBUTION IN BROWN PHASE OF SECONDARILY REWORKED CLAY, AND PHOSPHATE PEBBLES

q = quartz; c = chromite; p = perovskite; m = magnetite; z = zircon; l = leucoxene.
Brown Phase of Clay shown by solid line, Phosphate Pebbles by dashed line.

although the perovskite is consistently about 15 times the amount of the titanite, are nearly parallel. Leucoxene and chromite also have a parallelism but not so strikingly as the other two.

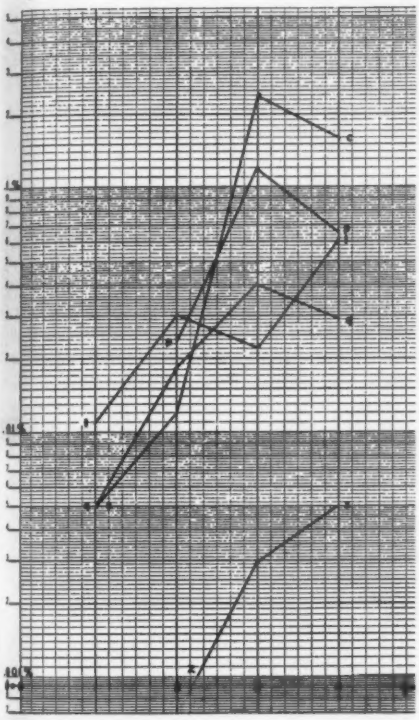

FIGURE 4. MINERAL DISTRIBUTION IN GRAY PHASE OF SECONDARILY REWORKED CLAY

q = quartz; c = chromite; p = perovskite; m = magnetite; z = zircon; l = leucoxene.

Figures 2 to 6.—Except in three instances, the magnetite in Figure 2, the zircon in Figure 3, and leucoxene in Figure 4, each of the lines has only one maximum. That leucoxene could be partly authigenic might explain its deviation from the main trend and, if this is the case, there is only magnetite and zircon. A definite shift of these maxima toward the smaller sizes also occurs, so that in the Brick and Chert they are all in the smallest size ($\phi = 4$) except for the leucoxene, where again its possible authigenic origin may be the cause. There is also a downward shift, that is, a decrease in the amount of the minerals in one graph to the next except for the quartz in Figure 3. The single maximum for almost every curve, the shift to a smaller size for this maximum, and

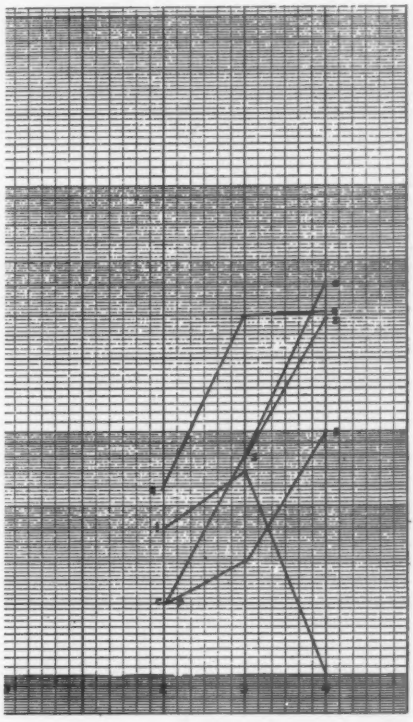

FIGURE 5. MINERAL DISTRIBUTION IN "BRICK"

q = quartz; c = chromite; p = perovskite; m = magnetite; z = zircon; l = leucoxene.

a decrease in its height was what might be expected if the minerals were derived from the same source and had been subjected to a longer period of erosion and weathering and solution.

The relative and actual amounts of the quartz and zircon are unexpectedly high in Figures 1 and 2 and also relatively high in Figure 5. In the Primary Red Clay and the Brown Phase, the total amount of these two species is over 1 per cent and that does not include grains less than a sixteenth of a millimeter.

Comparison of minerals from bore hole, clays,

and limestones.—All of the allogenic minerals found in the clays and limestones were also found in the weathered volcanics except for epidote, found only in the Primary Red Clay and in the "Brick" and there rarely. Its absence from the bore hole samples might readily be explained by the very small amount of material available for analysis. This same paucity of material would mean that the frequency of these minerals may have little significance. A few of the minerals seem to have disappeared completely, namely: melilite, nephelite, serpentine, barite, and the zeolites, as well as the volcanic glass and hypocrystalline material. Feldspar and the micas were rare in the clays. The pellets, common in the upper layers of the volcanics, were also common in the clays, but, being authigenic, they would be expected to increase rather than decrease.

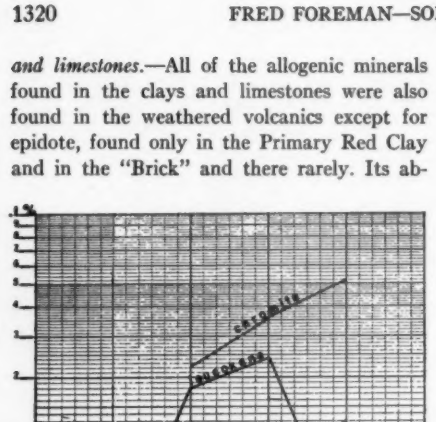

FIGURE 6. MINERAL DISTRIBUTION IN "CHERT"

Strangely enough, the upper part of the weathered volcanoes has the larger number of mineral species (Table 8). In the less weathered volcanics below the 665-foot level, the absence of certain minerals may be due to a change in the type of lava or to the smallness of the sample, or, as seems more likely, a mixing of the material in the upper layers, by the action of the waves or other agents, has brought mineral species from other lava types into the samples. In describing the minerals from the bore hole, a distinction was made between the minerals in the weathered lavas themselves and those free from any lava matrix. Quartz, garnet, and zircon were all in this group and practically all of the chromite, perovskite, and augite, while the weathered lavas contained most of the micas and feldspar and all of the nephelite, melilite, and zeolites. Some of these "separate" minerals might have come from the weathered lavas, but where they were found exclusively or predominantly in the "separate" group their presence would indicate that their source was other igneous rocks not penetrated by the bore hole. It would seem, then, that considerable mixing and weathering had occurred in the upper zone of the weathered volcanoes and little in the lower zones. One other feature of the separate minerals is that quartz and zircon were found as far down as the 695-foot level, where the lavas were only slightly altered, and this in spite of the very small samples that were available.

Effect of weathering on the minerals in the clay.—If the Primary Red Clay was the parent rock of the other clay samples, the shift in size and amount of the allogenic minerals toward smaller diameters and less total material was to be expected. The size distribution (Fig. 2) would be determined by the initial size of these minerals in the rocks from which they were derived, modified by the erosion and weathering they had undergone. Apart from the leucoxene, there was no indication of any secondary growth on these minerals, thus the modification would be in the direction of decreasing the individual size of the minerals and also decreasing the total amount to be found in the sieve sizes.

Except for the augite phenocrysts, Pirsson (1914) does not give the size of any of the minerals found in the unweathered lavas except in the most general descriptive terms. The weathered volcanics reported on above do not have the grade sizes tabulated because the spud drill had crushed some of the minerals, but they were separated into sieve sizes, many of which gave no indication of being broken. The majority of these were either in the one-quarter to one-eighth millimeter grades or in the one-

eighth to one-sixteenth millimeter grades. Few were over half a millimeter and none over one millimeter. Of course, fracturing by the spud drill would be most likely to affect the larger grains, but the rounded calcite fragments, generally much larger than any of these minerals, were often unbroken. The allogenic minerals in the Primary Red Clay were, for the most part, definitely coarser than the minerals found in the volcanics. This would indicate that there were other igneous rocks with coarser grain than those found by the drill core and that most of the igneous minerals of this clay were from such rocks. The other clays, with smaller grain size of allogenic minerals, may have been derived either from the Primary Red Clay by a further process of weathering which would, of course, decrease the size of grain, or they may have been derived directly from lavas such as the drill found. However, from the method of occurrence of these clays, the former process would seem to be the most probable.

As was pointed out above, almost the same mineral suite was found in the clays as was found in the weathered volcanics; the residues of the marine limestones above the clay contained no allogenic minerals not found in the clays. The petrology of the soil samples reported by Sayles (1931) contained practically the same minerals, the most noticeable difference being that zircon was one of the infrequent species and that miscellaneous grains of corundum, muscovite, staurolite, and hornblende were found which were not found in these clays.

Allogenic minerals.—Only two minerals, quartz and zircon, found in the clays might not be expected from the weathering of the lava types reported from the Gibbs Hill bore hole by Pirsson (1914). Sayles considered that the quartz found in the soils might have been brought to the island by birds, by jelly-like organic substance, and by tropical storms, and, because of its resistance to solution and the slight abrasive effects that the calcite sands of the eolianites would have on these grains, they have persisted and accumulated in the soils.

If the Primary Red Clay was as widespread as indicated by Moore and Moore, then the large amount of both quartz and zircon present would seem to point toward a different origin. Little seems to be definitely known as to whether birds show any selectivity in the choice of mineral grains, the effect of the action of the gizzard on these particles, or how long they may be kept in the gizzard. B. F. Kaupp (1924) kept hens for a year where they could not replenish the grit in their gizzards. Excess of the grit was passed out in the first few days and after that little was lost. The birds were healthy at the end of the year, and the grit in the gizzards at the end of that time was as sharp as at the start of the experiment. It might be expected that sea birds, because of their long flights away from the land, would be more conservative with their grit than hens, which usually have an immediate supply near-by. Groebbels (1932) in his classic work on birds says little about their selectivity, but he mentions that they are not limited to stone and sand material; wire cloth, glass, coal, brick, mortar, and soil had been found in the gizzards. There would seem to be no reason to expect the birds that came to Bermuda to bring only quartz and zircon to the exclusion of other minerals or that only these two minerals have been preserved, since the rest of the mineral suite of the clays are generally considered as somewhat unstable. Anyway, the very large amount of quartz and zircon (which totalled over 1.2 per cent) found in the Primary Red Clay would seem to demand some other origin than those indicated by Sayles.

Magnetic declination and latitude observation made by V. F. Cole (1908) in the Bermudas found some six roughly circular areas from one-half to 2 miles in diameter whose values were less than normal for the area; these abnormalities could be interpreted as indicating rocks lower in magnetite than the surrounding areas and therefore possibly more acid. Woolard and Ewing (1939), making observations on the vertical component of the magnetic field, found very high local positive and negative disturbances. While too incomplete for final conclusions, the work did indicate that these disturbances were near the surface but were not due to artificial causes. Professor G. P. Woolard (personal communication) stated that these areas may be volcanic pipes of possible andesitic or trachytic composition. Young (1939) found fragments of sanidine-bearing, trachytic, volcanic rock with augite phenocrysts and acid

plagioclase in deep-sea cores to the east of the island and these fragments were thought to have come from volcanoes of the Bermuda area. There appears, then, to be a possible source for these minerals in the igneous rocks themselves; if the basic minerals could find their way into the eolianites, the more stable quartz and zircon should be able to do the same, if any of the igneous rocks below the limestones carried these minerals.

The observations of Harrison (1933) indicate that part of the quartz may be secondary, the result of the lateritization process. Regarding the lateritization of the Tumatumari dolerite (Table 10 shows that the Primary laterite phase, weathered from this rock, contains 12.24 per cent silica), he states (p. 20–21):

> "It is evident that, during the course of lateritization under the conditions prevalent at Tumatumari, a portion of the silica set free assumes the form of quartz. Assuming that, in the inner layers of primary laterite, the alumina is the static constituent, about 10 per cent of the laterite of the innermost layer, and about 9 per cent of the middle completely lateritized layers, is secondary quartz."

This seems to be a general process in the humid tropical Guiana area and may account for at least part of the quartz in the soils and clay of Bermuda. Many grains, as noted above, show vugs and cavities, a likely indication of their secondary origin.

This is not to imply that no foreign grains were brought to the island and by agents indicated by Sayles. A few of the quartz grains were well rounded and frosted, an effect that could hardly have happened on the island unless it might be due to solution (Pettijohn, 1949, p. 58). Some of these grains were in the one-half to one millimeter size, which would seem too large for wind transportation over such great distances. There were zircon grains, too, that were well rounded and the fact that except for rare grains, only these two minerals were different to those that might be expected from the known volcanics of the area, and that these two were in such large amounts makes it unlikely that there could have been such high selectivity by any transporting agents that might have brought sand grains to the island.

Perovskite, the commonest allogenic mineral in the Primary Red Clay, seems to be very uncommon in sediments. Neither Milner (1940) nor Krumbein and Pettijohn (1936) mention it in their sedimentary petrologies, and Boswell (1933) has only two references to it. Larsen found it to be one of the common minerals in the soils between the eolianites (Sayles, 1931, Table V), and it evidently reflects the unusual lavas of the underlying volcanics. The striated surface texture common in many of the grains as well as the partial or complete coating by leucoxene would point to solution as an active agent during weathering and also after the clay has been submerged by marine waters. Figure 1 shows a very regular rate of decrease in amount of this mineral in the derivatives of the clay and accompanying this is also a steady shift of the maximum to the smaller sizes (Figs. 2–6).

Chromite was not mentioned by Sayles (1931) as one of the minerals in the soils between the eolianites nor by Pirsson (1914) as in the lavas, but both found *magnetite* to be common. If the melilite basalts are among the most important rock types in the lavas, then chromite should be expected. Iddings (1913) lists chromite as one of the essential minerals with melilite, olivine, and pyroxene, and Johannsen (1938, p. 347) also notes it as one of the common minerals in the groundmass of these rocks along with magnetite, chrome spinel, perovskite, and apatite. Magnetite was fairly common in the weathered volcanics and the Primary Red Clay but becomes infrequent in the derivative clays, while chromite was much more stable and although not as common in the weathered volcanics as magnetite, it was much more common in the Primary Red Clay and was one of the dominant minerals in the other clays (Tables 2–6).

Augite was found in all the Bermuda sediments, in the lower weathered volcanics, and in the unweathered lavas as well as in the deep sea cores to the east of the island (Young, 1939). Although generally listed as a typical unstable mineral in sediments, it showed little evidence of weathering except hacksaw (coxcomb) terminations (Pl. 2, fig. 2), characteristic of this mineral in all samples of the above-listed sediments. This feature is ascribed to intrastratal solution effects (Pettijohn, 1949). Ross, Meiner, and Stephenson (1928) found the same phe-

nomenon in Upper Cretaceous water laid volcanic rocks, but here each of the augite crystals was surrounded by a zone of glauconite material that marked the original boundary of the grain. This altered zone has not been reported in the Bermuda area. The source of this mineral was likely the underlying volcanic rocks; explosive eruptions may have accompanied the flows to furnish those particles found in the deep sea cores.

Little need be said about the other allogenic minerals. The titanite was much more common in the Primary Red Clay than in the others. Pirsson (1914), who found it in the underlying lavas, considered it an alteration product of the perovskite, but it is commonly found in intermediate and acid rocks and is regarded as allogenic in these clays. The epidote, garnet, and mica were all uncommon minerals in the clays; they were also found by Larsen in the soils (Sayles, 1931).

Authigenic minerals.—It is difficult with a sediment like the Primary Red Clay, where subaerial weathering was followed by invasion of marine waters without any noticeable sorting of the sediment, to separate those minerals which were authigenic in the earlier subaerial environment from those which were authigenic to the later marine environment. This is made still more difficult because the weathered volcanics from which the soil was formed may also have been subjected to both subaerial and marine conditions. For these reasons, those minerals found in the lavas will be called allogenic and all others, unless of foreign origin, will be placed in the authigenic group.

PELLETS OF PHOSPHATIC CALCAREOUS IRON OXIDES: The material from the bore hole commonly contained iron oxide as brown earthy pellets in the upper zones above the 583 foot level. Coatings of iron oxide and calcite were present on nearly all the minerals and on the weathered volcanic glass. Pirsson considered that this phase of the volcanics was the debris from subaerial weathering of the volcano, later spread out by the action of the waves as planation of the island was accomplished. The calcite was deposited with the weathered rock as it was being sorted by the waves to give the "calcite balls" and brown earthy calcareous material. It would seem then that carcareous iron oxide pellets may easily have been formed by the above processes and is, therefore, partly subaerial and partly diagenetic in origin.

PHOSPHATIC MATERIAL: Table 9 shows that phosphate was common in all the clays except the Gray Phase of the Secondarily Reworked Clay and that it was also present in lesser amounts in the overlying marine limestone. Collophanite, the only mineral recognized, has been described by Frondel (1943) as structurally identical with apatite, its isotropic character due to its fine-grained metacolloidal texture and its variable index to non-essential water. The origin of this mineral would appear to be from the leaching of guano. Sayles (1931) found pebbles of collophanite in a cave at Stokes Point; these were evidently much the same as those found in the Brown Phase of the Secondarily Reworked Clay and no doubt such solution and redeposition has been occurring since the first of the limestones were formed. Reiche (1945) claims that when coagels are formed from the drying of colloidal suspensions, silica, alumina, ferric, and ferrous oxides, and phosphates are often included in the complex. The "Brick" and "Chert" probably owed their peculiar porcellaneous character to some such complex and one in which the phosphate was one of the major ingredients.

Silt.—The material that passed the one-sixteenth millimeter sieves contained the silt, the clay, and the colloid material. In Table 1 are recorded the textural analyses of the clays of which only the first three, the Primary Red Clay and the Brown and Gray phases of the Secondarily Reworked Clays, were carried beyond the sieve grades. Much of the material in the silt sizes were iron oxides. Microscopic study of the silt particles which had been separated from the clay portion by decantation showed that the same minerals were present in these sizes that were present in the finest sand grade and in about the same proportions with the exception that the brown iron oxide particles were much more plentiful.

Clay and colloidal material.—These formed the bulk of the clays and were the most complex phase of these sediments, and, because of their fine size, the most difficult to analyze. In each case these were a mixture of residual products, fragments of the more resistant min-

erals, and chemical additions comprising the carbonate, phosphate, and iron oxides. Under the microscope, even at a magnification of ×1000, the greatest part of the material was isotropic or nearly so and apparently amorphous. Present-day investigation of soils indicate that even the finest phases of clay are crystalline. Because of the platy nature of the mica-like lattice structure of the clay minerals and the extremely small size of most of these crystals, the surface effects are such that in solution the unbalanced charge of the surface atoms attracts cations of various kinds. How the cations are held is not yet fully known, but recent studies (Kelly, 1946) indicate that the bond is only partially covalent, and that instead of OH ions being adsorbed and then the cations in turn adsorbed by these unbalanced hydroxide ions, the cations are held directly by the unbalanced charge of the lattice. The commonest cations in soils are those of H, K, Mg, Na, and Ca; other less common cations and radicals may at times be important, one of which is the phosphate radical. The base-exchange capacity of the clay minerals for various cations and radicals is variable and the whole process is exceedingly complex. W. P. Kelly, W. H. Dore, and S. M. Brown (1931) found that replaceable bases are found in the interior of these crystals of colloidal size as well as on their surfaces and these bases are an integral part of the chemical constitution of the crystals.

The refractive indices of the clays were higher than those usually recorded. These indices ranged from 1.580 to 1.645 for the matrix and from 1.65 to 1.98 for the granules. The upper limit was about the same for all the clays, but the lower was variable. Optical examination of material which is beyond the resolution of the microscope will not show the birefringence of minute crystals except as an aggregate effect, giving a slight grayish tinge to the field of the microscope. This effect was observable in material that had not been treated with dilute hydrochloric acid, but after such treatment, except for occasional flakes of gibbsite (?) and fragments of zircon and quartz, the material seemed quite isotropic except where the amount of iron oxide was large or where the small oölith-like bodies occurred, then a very slight aggregate effect could be seen. As noted before, the indices and very low or absence of birefringence suggest that this material may be halloysite. Ross and Kerr (1935) have given the optical properties for some 23 samples of halloysite, whose indices of refraction ranged from 1.546 to 1.648. The material with the highest index contained iron oxide which, according to the authors, was likely responsible for its unusually high index of refraction. They also found gibbsite associated with the halloysite in some samples and concluded that this supported the evidence that halloysite was the result of weathering.

Phosphate may be either adsorbed or precipitated (Kurtz, de Turk, and Bray, 1946). When adsorbed it may replace the silica to a considerable extent, forming a colloid of high PO_4 content and low in silica (Mattson, 1931). Submicroscopic crystals of collophanite were found by Frondel (1943) in the phosphatic rocks of the West Indies islands precipitated from solution of guano in overlying rocks. In the Bermuda clays both adsorption and precipitation seem to have occurred, and in those high in phosphate the collophanite is variable. The refractive index also varies; these indices were in the same range as that of the clays and, as both are apparently isotropic, it was impossible to differentiate the collophanite from the clay colloid by optical methods.

The role of titanium in clays is not well known, but it does accumulate in residual soils to a surprising amount. Wentworth *et al* (1940) found up to 15 per cent of titania in the Ceramic clays of Hawaii which were apparently derived from basalts carrying from 1½ to 4 per cent TiO_2. In the Columbia River region, igneous rocks that averaged 1.7 per cent titania gave rise to residual soils carrying over 7 per cent of this oxide (Allen and Nichols, 1946).

Most authors assume titanium occurs either as leucoxene or as ilmenite, but Polynov (1937, p. 115) thinks that it may enter "complex aluminosilicic colloidal systems together with silica and sesquioxides." How the titanium was contained in these clays could not be ascertained. No leucoxene, ilmenite, or any other recognizable mineral was found in the finer portion, but it may be that their high refractive indices were partly due to titania adsorbed by the clay.

F. Hardy (1931) used alizarin absorption to determine the "free alumina" in a number of tropical soils and found that Bermuda Red Soil contained a greater amount of this free alumina (11.2 per cent) than soils from a number of localities from islands in the West Indies, the East Indies, and Hawaii. This Red Soil was evidently one of the inter-eolianite soils, but no mention was made of its horizon or locality other than that it was from Bermuda. However, since the same mineral suite was found by Sayles (1931) in the soils as have been found in these clays and there was likely little difference in the climates when the clays were formed and when the soils were accumulated, it can be expected that alumina would have the same role in both the soils and the clay. Whether the alumina is "free" or whether, as Robinson suggests, the sesquioxides may be lightly combined but extractable by the peptization effects of aluminum chloride is at present not known. Colloidal compounds containing aluminum, iron, silicon, and phosphorus were examined by Mattson (1931, p. 318) and he states: "*It seems quite obvious that we are dealing with colloidal complexes represented by a continuous gradation in composition as well as in properties.*" The italics are by Mattson. Mattson's statement may well apply to the colloids in these clays.

Iron oxide and hydroxides were found in all phases of the clays, their color indicating the ferric condition except in the Gray phase of the Secondarily Reworked Clay whose slate-gray color indicated that it had been subjected to reducing conditions. This is supported by the presence of pyrite in this clay, some of it coating the foraminifera tests, and also by the occasional glauconite grains. There was no suggestion of organic matter in the clay apart from the slight amount of shell fragments, so it would seem that this reduction was due to conditions that were probably local in which oxygen was lacking and hydrogen sulphide was present.

The presence of the calcite pseudomorphs after gypsum in the Brown Phase of the Secondarily Reworked Clay indicates changing environment after the clay had been deposited. Such large gypsum crystals would not be due to precipitation from open sea water but likely followed the oxidation of pyrite to sulphuric acid which in turn reacted with calcite to form gypsum. If this was the case, there would be initial reducing conditions in which hydrogen sulphide accumulated from which the pyrite was formed. This in turn was oxidized to form sulphuric acid and the reaction of this acid with the calcite under suitable conditions would result in gypsum.

The concentration of some of the iron into the small sub-oölith-like bodies which were scattered through all the clays, even the Gray phase of the Secondarily Reworked Clay, might be the initial phase in the forming of the pisolitic bodies that are common in some lateritic clays. The greater part of these iron compounds, however, were still dispersed through the clays and gave them their color.

Chemical analysis of the Primary Red Clay.—Column 1 of Table 10 gives an analysis of the Primary Red Clay[1] after the limestone pebbles had been removed. This analysis is not complete, but it covers the main elements of the clay. The only known analysis of the igneous rock of Bermuda is presented in column 2. Pirsson (1914) considered this to be a mixture of melilite basalt and monchiquite lavas which had been somewhat altered and, for this reason and also because the amount of material available was very small, did not think it too satisfactory. An analysis of the St. George's Red soil given by Sayles (1931, p. 444) (column 3) was from a deep-red phase taken from a hollow. This is the only analysis of the interglacial Bermuda soils that seems to be in any way comparable to the Primary Red Clay. Columns 4 and 5 are of a dolerite and its weathered phase, respectively, from the Hope Quarry near Kamaru, New Guiana studies by Harrison (1933). Column 5 is an average of four analyses from the upper 2½ inches of the weathered phase of 4 and called by Harrison a Primary Laterite of the Low Level type.

A recast of the Primary Red Clay analysis in which the phosphate, magnesia, and lime are left out, is given in column 6. This was done

[1] The author is indebted to the Reynolds Mining Corporation of Little Rock, Arkansas for this analysis. It was made by the sodium carbonate fusion method at the Research Laboratories of the Reynolds Metals Company, Sheffield, Alabama.

on the assumption that these oxides may have been added to the clay after it had formed and were therefore unwanted when the analysis was high percentage of lime, and the presence of carbon dioxide. The Guiana rock had weathered under a climate that was no doubt more tropical

TABLE 10.—CHEMICAL ANALYSES

	1	2	3	4	5	6
SiO_2	12.18	38.79	28.68	51.09	20.44	16.04
Al_2O_3	21.96	14.55	26.24	15.70	29.10	29.02
Fe_2O_3	12.46	5.67	12.09	1.68	25.92	16.42
FeO		6.68		8.57	2.65	
MgO	1.74	7.78	1.72	7.74	0.42	
CaO	8.31	14.65	3.13	9.11	0.28	
K_2O		2.54	0.73	1.55	0.18	
Na_2O		2.78	0.77	2.38	0.31	
TiO_2	7.82	0.80	1.58	1.70	4.94	10.32
P_2O_5	14.14		0.50	0.01	0.01	
CO_2	(1.05)	3.56	2.03	nil	nil	
SO_3			0.26			
Cl			0.28			
MnO	0.02		0.25	0.41	nil	0.02
H_2O		2.66	21.80	0.35	15.98	
Loss on ignition	15.03					19.83
Balance	6.34					8.35
Total	100.00	100.46	100.06	100.29	100.23	100.00

1. Primary Red Clay. Analysis by Reynolds Metals Company Research Laboratory, Sheffield, Alabama.

2. Melilite—basalt mixed with some monchiquite from bored well, at 1110 feet, one mile west of Gibbs Hill (Pirsson, 1914, p. 341).

3. St. George's Red Soil, Bermuda Island (Sayles, 1931, p. 444).

4. Dolerite, Hope Quarry near Kumaru, British Guiana (Harrison, 1933, p. 22) Table 11, Column 1.

5. Primary laterite, Hope Quarry near Kumaru, British Guiana. Average of four analyses, Table 11, Columns 2, 3, 4, and 5, giving the upper 2½ inches of Hope Quarry Laterite, weathered from Dolerite given in 4 (Harrison, 1933, p. 22). In the original analysis quartz is given separate from the SiO_2. This quartz is added to the SiO_2 in making the average SiO_2 for this analysis.

6. Recase analysis of Primary Red Clay with the phosphorus, calcium, and magnesium oxides left out.

to be compared to rocks in which no such additions had been made.

DISCUSSION OF ANALYSES: No analyses of a parent rock of melitite basalt or of monchiquite composition and its weathered derivative was known to the author, so the analyses of a somewhat similar rock, a Guiana Dolerite, and its weathered phase was chosen. The silica in column 4 is decidedly higher than that of 2, but the other oxides are in much the same proportions, especially the more significant ones, the aluminum and iron. It should be kept in mind that the rock given in column 2 had undergone some alteration and addition shown in the large amount of ferric iron, the and humid than Bermuda, but this was likely balanced by the lower silica and glassy nature of the Bermuda lavas.

Columns 5 and 6 are much alike except for the higher content of iron oxide in the laterite from the dolerite and the much higher titania content of the Bermuda clay. The alumina content of each is almost the same as is the ratio of the silica in the parent rock to the weathered derivative in each case. If then the Guiana laterite is due to weathering under a tropical humid climate, the Primary Red Clay was probably formed under similar conditions.

Since the analysis of the Bermuda lavas was made from an altered rock and also from a

small sample, no attempt will be made to trace the changes from lavas to the clay. One thing only will be mentioned, and this because of the extremely high content of titania in the Primary Red Clay. The titania content of the lava analysis is very low compared to most analyses of melilite basalt or monchiquite rocks (Johannsen, 1938, Tables 126 and 133), and it is most probable that there are other Bermudian lavas in which the titania was much more plentiful.

In the recast clay analysis (column 6), the Si–Al ratio (molecular) is 0.94, that of the soil (column 3), 1.87, and that of the Bermuda lava 4.55. If the ratio of Si–Al of 1.33 or less is taken to indicate a laterite (Martin and Doyne, 1927), then the Primary Red Clay must be classed as such, while following the same authors, the St. George's Red soil would be a lateritic soil as its ratio is between 1.33 and 2.0. In the clay the analysts reported that 63 per cent of the alumina was soluble under standard American Bayer conditions showing that this percentage was present as the hydroxide.

ADDITIONS TO THE PRIMARY RED CLAY: The analysis of the Clay was recast leaving out the phosphate, magnesia, and lime on the supposition that all these were in the collophanite of the clay. No analysis of a laterite clay known to the author shows a phosphate content comparable to this clay, and as the primary rock from which it came does not carry an unusual amount of phosphate, it is obvious that it must have been introduced after the clay had formed and under quite different conditions to those which gave rise to the clay.

Frondel (1943) in his study of the Insular Phosphate Rock of the West Indies showed that the mineral collophanite was a fine-grained metacolloidal variety of the apatite group containing some carbon dioxide, some "essential (OH) together with an indefinite amount of absorbed and capillary water." Collophanite as shown above was found in these sediments. If we take the analysis of this mineral that Sandberger obtained and cited by Frondel (1943, p. 219) and if we suppose that Mg can proxy for Ca in the atomic structure of the mineral, we would have an equivalent of 10.75 per cent of CaO from the lime and magnesia of the clay analysis. If the same is done with the Sandberger analysis, it gives a total of 51.82 per cent of CaO. If now an equivalent amount of phosphate is allotted to the lime of the clay analysis that the collophanite analysis shows, it would use up 8.11 per cent of the P_2O_5 of the clay. This still leaves 6.03 per cent of the phosphate unaccounted for; this percentage would be even larger if, as is likely, little or none of the Mg was in the collophanite structure. It also explains why the magnesia and lime as well as the phosphate were subtracted in the recast analysis of the clay, on the supposition that as much of the phosphate as possible was in the form of collophanite.

The role of the remaining phosphate in the clay is not known with any certainty. Soil scientists have given considerable attention to the fixation of phosphate in soils. Swenson, Cole, and Sieling (1949) found that phosphate will combine at low pH values (3.5–4) with hydrous oxides of aluminum and at pH of 2.5 to 3.5 with hydrous oxides of iron. However, this high acidity would seem to be more than could be expected for the environment under which this clay had formed. Stout (1939) found that kaolinite and halloysite, when in a very fine state of subdivision of the order of one micron or less, did fix considerable phosphate. His interpretation was that the phosphate ions replaced the OH ions in the clay. Coleman (1944), working on the same problem using kaolinitic and montmorillonitic clay, concluded that (p. 76): "In the fine clay fraction most of the phosphate is fixed by these oxides (oxides of aluminum and iron) and in the coarse fraction all the phosphate is fixed by them." Still other interpretations might be cited but the above are enough to indicate the differences of opinion regarding this problem at the present time.

From the above it is evident that the Primary Red Clay was formed from the volcanics of Bermuda under conditions of subaerial weathering in a humid tropical climate and after the clay had formed the phosphatic material was added. Part of the phosphate is in the form of the mineral collophanite, but the role the rest plays in the clay has not been determined, although it is likely related to the unbalanced charges on the clay particles and to the replacement of certain ions in the lattice of the clay.

Tentative History of Bermuda from the Study of These Rocks

An outline of the history of Bermuda covering the interval from the time of the weathered volcanics to the surface rocks can only be tentative at the present time. The evidence of the bore hole with its thickness of 245 feet of chalky Bermuda limestone between sea level and the top of the weathered volcanics and the evidence of the two seismic refraction depth profiles made by Woolard and Ewing (1939), which they interpreted as showing that the tops of the volcanics were at depths of 273 and 243 feet, respectively, would suggest that planation of the island had occurred likely late in the Tertiary. This concept of wave planation of the island before the limestones were deposited is similar to that held by Pirsson (1914), Sayles (1931), and Daly (1934). Daly interpreted the planation to indicate a time of several million years of crustal stability for the area during which the platform with its area of 250 square miles was made.

Opposed to long-continued stability of volcanic islands are Darwin (1837), Dana (1849), Davis (1928), and Shephard (1948), to mention only some of the more outstanding workers on this problem. These men favor subsidence as one of the main factors in the building of coral islands of the barrier and atoll reef types. Davis (p. 213) points out that platforms such as Bermuda are almost unknown even in the cooler parts of the Pacific Ocean where there are no reefs to protect the shores from wave erosion.

Whether barrier and atoll types of reef were common and vigorous before the Pleistocene Epoch is also a moot question and again Daly and Davis have opposite views. Daly (p. 236) writes: "There is no evidence that either kind of reef existed until the first Interglacial stage when the platforms were already developed". Davis (p. 214) states: "and its (Bermuda) bank would appear to represent the remains of a former atoll of vigorous growth in a period of higher temperature than now." We have then divergent explanations of almost every phase in the history of the island.

What environment or environments will produce a sediment such as the Primary Red Clay? This lateritic clay, whose texture is similar to a residual clay, carries some marine fossils of foraminifera and sponge spicules and an exceptionally high percentage of phosphate and titania would seem to be the result of a sequence of rather unusual conditions. The first condition would be that of subaerial weathering for a considerable time under a humid tropical climate to give a lateritic clay high in titania. The second would be a marine invasion of such a type that the clay was not reworked by the waves to any degree. The third would be an environment favorable to the introduction of the phosphate into the clay. These conditions would be fulfilled if at least part of the volcanics of the platform were above sea level under a climate much like the present one. How long this weathering would take is not known, but from the evidence of the fossil earths between the eolianites it was longer than could be accomplished in one interglacial age and therefore was Prepleistocene. If these areas above the sea were protected by a barrier reef and if, after the clay had formed, subsidence occurred and the reefs were able to maintain their position by upward growth and continue to break the force of the ocean waves and the clay inundated by the marine waters but not reworked by them to any extent, the first two conditions would be fulfilled. In a lagoon of what would now be an atoll reef, the phosphatic material would be available from the solution and precipitation of phosphate from both the vertebrate and invertebrate forms which are unusually abundant in lagoon waters. It is possible that part of the phosphate may have been leached from the overlying limestones, but there seems no way of determining this from the clay itself.

It is possible to account for the Brown and Gray phases of the Secondarily Reworked Clay if the floor of the lagoon was irregular and there were some basins in which the water was stagnant and gave reducing conditions and others in which the environment was variable so that both reduction and oxidation took place. The Gray Phase with its reduced iron, glauconite grains, and authigenic pyrite is suggestive of stagnant basins and the Brown Phase, by its friable nature, suggests oxidized iron and

the pseudomorphs of calcite after gypsum of alternating conditions.

Both the "Brick" and "Chert" may be regarded as products of local conditions where a very high concentration of phosphatic material gave the rock its peculiar characteristics. This shallow lagoon condition was evidently followed by a rather sudden deepening of the waters over the platform and the first marine limestone, the Cladocora rock, was deposited. In progressively shallower waters, the other limestones were laid down until shallow lagoon conditions were again reached when the "sandstone" was deposited. All the later rocks indicate different phases of shallow and littoral conditions which persisted until the Brachydontes Rock, the uppermost of the limestones found, had been laid down. The ecology of these limestones and its interpretation has been outlined by Moore and Moore (1946) and their interpretation agrees with the observations of the author.

Summary

Material from the Primary Red Clay and its derivatives, the Secondarily Reworked Clay, the "Brick" and the "Chert", and from the overlying marine limestone of the Castle Harbour area, Bermuda, as well as some of the weathered volcanics from the Gibbs Hill bore hole have been examined texturally and petrographically in an attempt to learn something of the history of the island between the time of the lava flows and the surface eolianites. It would appear that this clay was a soil formed under humid, tropical, or near tropical conditions and carrying an abundant suite of the more persistent minerals of the lavas. The stratification, texture, and composition of the clay indicate a rather long period of weathering of surface igneous rocks among which were late intrusions of a more acidic nature from which the quartz and zircon were possibly derived. Submergence under lagoon conditions allowed the clay to maintain its soil-like characteristics and also provided an environment in which large amounts of phosphate were added to the clay; above this clay, the marine limestones were deposited. It would appear that the clay and possibly the marine limestones were formed during late Tertiary times.

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OLDER PRECAMBRIAN STRUCTURE IN ARIZONA

BY CHARLES A. ANDERSON

ABSTRACT

The older Precambrian rocks of Arizona include the Vishnu, Yavapai, and Pinal schists, all overlain unconformably by nonmetamorphosed younger Precambrian rocks. The older Precambrian schists, unnamed gneisses, and associated granitic masses crop out in many of the mountain ranges southwest of the Colorado plateau.

The stratigraphy and structure of the schists can be unraveled to some extent by detailed mapping, and work now in progress by the U. S. Geological Survey in the Bagdad, Prescott-Jerome, and Little Dragoon areas, is revealing folded structures trending generally northwest to northeast. Earlier work by Wilson in the Mazatzal Mountains revealed southeastward-dipping, low-angle thrust faults of older Precambrian age.

In the Bagdad and Prescott-Jerome areas, a variety of igneous rocks, including rhyolite, alaskite porphyry, diorite, and gabbro, were intruded into the schists prior to the widespread invasion of granite. Only one period of orogeny followed by the intrusion of granitic rocks can be recognized in each area studied to date.

The degree of metamorphism is not uniform and some of the pre-intrusive rocks are nonfoliated, whereas others are highly schistose. Some of the intrusive rocks, including granite, show the effect of dynamic metamorphism. The grade of metamorphism is low to intermediate, except near the large masses of granite where coarse-grained sillimanite-bearing schists are found.

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INTRODUCTION

Only meager information is available pertaining to the early structural history of Arizona, although the distribution and general character of the Precambrian rocks has long been recognized. The purpose of this paper is to present samples of the types of structural information that can be obtained from detailed studies of

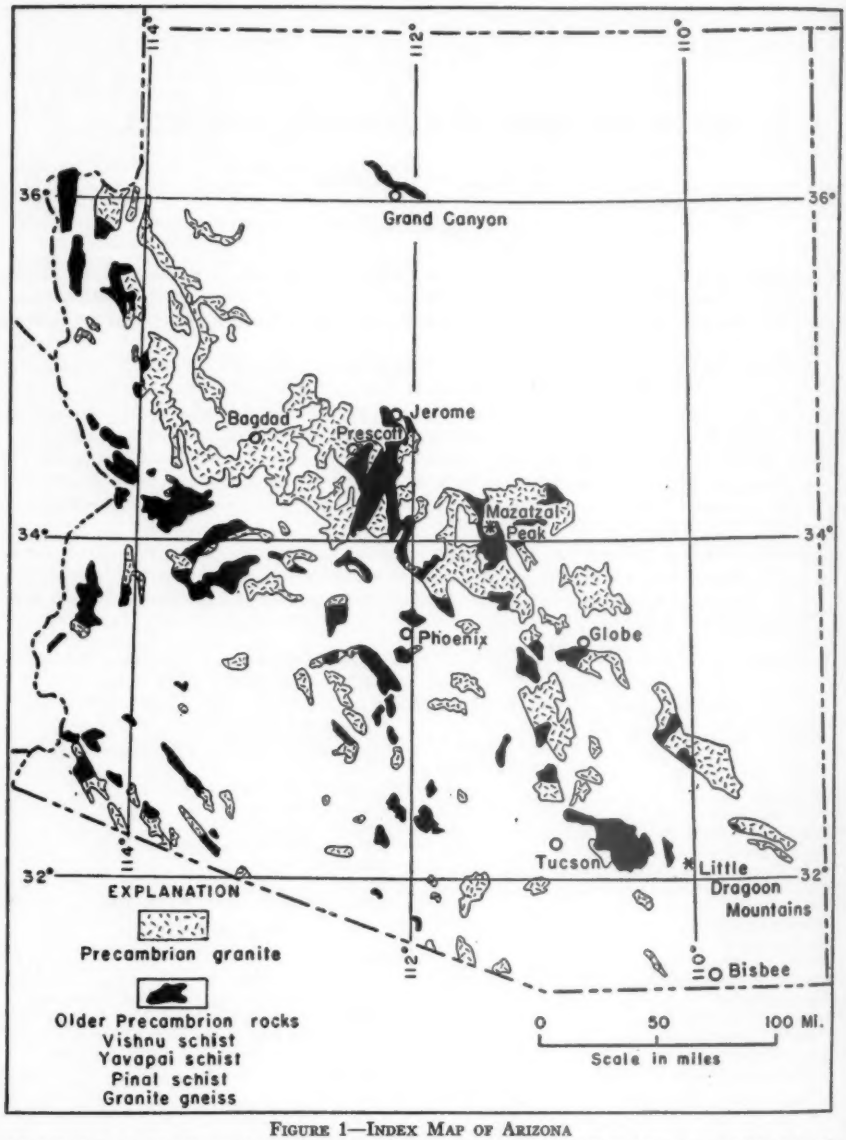

FIGURE 1—INDEX MAP OF ARIZONA

Distribution of older Precambrian rocks copied from Tectonic Map of United States, published by the American Association of Petroleum Geologists, 1944.

the older Precambrian rocks in which the stratigraphy can be determined. The first successful attempt was made by Wilson (1939) in the Mazatzal Mountains of central Arizona, and a summary statement of his work is included. The other samples were obtained from work now in progress or recently completed by members of the U. S. Geological Survey. The areas of these

samples are the Little Dragoon Mountains in southeastern Arizona and the Bagdad and Prescott-Jerome areas in central Arizona (Fig. 1).

this paper, include the Vishnu schist of the Grand Canyon, Yavapai schist of central Arizona, the Pinal schist in southeastern Arizona,

TABLE 1.—CORRELATION TABLE OF PRECAMBRIAN ROCKS OF ARIZONA

	Grand Canyon (Noble and Hunter, 1917; Darton, 1925)	Bradshaw Mts. (Lindgren, 1926)	Mazatzal Mts. (Wilson, 1939)	Globe (Ransome, 1903)
Younger Precambrian	Grand Canyon series: Chuar group, Unkar group	Unconformity	Apache group	Apache group
	Orogeny—intrusion of granitoid magmas			
Older Precambrian	Vishnu schist	Yavapai schist	Yavapai group: Mazatzal quartzite, Maverick shale, Deadman quartzite, Alder series, Red Rock rhyolite, Yaeger greenstone	Pinal schist

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Thanks are due John R. Cooper for data on the Little Dragoon Mountains, and to M. H. Krieger and W. H. Eckstein for information in the Prescott area. To my associate in the Jerome study, S. C. Creasey, I am greatly indebted for much of the factual information in this paper pertaining to the Jerome area. Our mutual discussions over a 4-year period on the general problems relating to the older Precambrian rocks have helped to crystallize and clarify many of the conclusions. R. S. Cannon, Jr. has contributed much in the field and office in discussing the structural problems of the older Precambrian rocks. The manuscript has been improved by the helpful comments of J. R. Cooper, S. C. Creasey, W. H. Eckstein, and E. D. Wilson.

PRECAMBRIAN ROCKS OF ARIZONA

General Statement

The Precambrian rocks of Arizona belong to two major systems, commonly termed Archean and Algonkian, but Butler and Wilson (1938, p. 11) have referred to them as older and younger Precambrian, a preferable designation. The older Precambrian rocks, the subject of and also unnamed gneisses in southern and western Arizona (Table 1). The schists and gneisses have been intruded as many places by granitic rocks. The younger Precambrian rocks include the Apache group of sediments and basalt flows, exposed in central to southeastern Arizona, and the Grand Canyon series (Unkar and Chuar groups), that crop out in the Grand Canyon. These younger Precambrian rocks rest unconformably on the older Precambrian schists and granitic rocks and are unmetamorphosed except adjacent to Mesozoic granitic rocks.

Older Precambrian Rocks

The Vishnu schist of the Grand Canyon, first described by Walcott (1890), includes schist and gneiss, according to Noble and Hunter (1917), who suggested that at some future time it might be desirable to restrict the name "Vishnu schist" to the mica schists and give new names to the gneiss. Campbell and Maxson (1938) proposed that the term "Vishnu schist" be discarded and that "Vishnu series" be used for the 25,000 feet of metasediments exposed in the Grand Canyon. Original fine-grained argillaceous sandstones and sandy shales have been metamorphosed to quartzites, sericite-quartzites, and quartz-mica schists. In addition, they recognized a sequence of basaltic lavas and

tuffs, now represented by amphibolites, in which relict pillow and amygdaloidal structures prove the volcanic character. No name was given by Campbell and Maxson for the metavolcanic rocks, and a general term is needed for the metamorphic rocks in the Grand Canyon. Until Campbell and Maxson complete their studies, it is desirable to retain "Vishnu schist" for all the metasediments and metavolcanics older than the Grand Canyon series. The Vishnu schist was intruded by plutonic rocks that range from quartz diorite to granite.

Ransome (1903) first described and defined the Pinal schist in the Globe area as crystalline schist of Precambrian age, derived in part from quartzose sediments and intruded by granitic rocks that are in turn unconformably overlain by the Apache group. In the Bisbee area (Fig. 1), Pinal schist lying unconformably below Cambrian sediments was recognized by Ransome (1904).

The Yavapai schist was first described by Jaggar and Palache (1905) from the Bradshaw Mountains, southeast of Prescott. According to them, the rocks include slate, phyllite, mica schist, and chlorite schist, and also local gneiss, granulite, hornfels, and hornblende schist. They concluded that the formation is of sedimentary origin and equivalent to the Vishnu schist in the Grand Canyon. The Yavapai schist also was intruded by Precambrian granitic rocks. Lindgren (1926, p. 15–20) recognized rhyolitic and basaltic flows in the Yavapai schist of the Bradshaw Mountains and concluded that the Yavapai schist comprises a series of sedimentary beds and a large amount of interbedded flows and tuffs. He also extended the Yavapai schist into the Jerome area where volcanic rocks are common. Lindgren suggested that the Pinal Yavapai, and Vishnu schists represent the same general formation (Table 1).

In the vicinity of Mazatzal Peak, Wilson (1939) subdivided the Yavapai schist into three formations: the Yaeger greenstone, intermediate to mafic flows, tuffs, and interbeds of sedimentary material; the Red Rock rhyolite; and the Alder series of sediments. Wilson also recognized three formations younger than the Yavapai schist: the Deadman quartzite, the Maverick shale, and the Mazatzal quartzite. The Yavapai schist and younger formations were folded, faulted, and intruded by granite before the deposition of the overlying Apache group.

Little Dragoon Mountains

Geologic mapping of the Little Dragoon Mountains, 60 miles east of Tucson (Fig. 1), on a scale of 1/24,000, is a current project of the U. S. Geological Survey under the direction of J. R. Cooper. The major problem has been the study of the stratigraphy and structure of the Apache group and of the Paleozoic and Mesozoic systems.

The Pinal schist is exposed unconformably below the Apache sediments (Fig. 2) and has been separated into five lithologic units by J. R. Cooper and F. W. Farwell: (1) Greenstone, composed of amphibolite with a chlorite schist facies at the margins, probably representing a series of mafic flows or intrusives, or both. Relict structures are not well preserved, but a few amygdules suggest a flow origin, in part. (2) Rhyolite, as represented in the area of Figure 2, is probably a single flow with a massive facies overlain by a flow-breccia top. (3) A complex of quartz-feldspathic sediments (arkose) and interbeds of sericite schist. Relict bedding is commonly present. Graded bedding can be used locally to determine the tops of beds. Rhyolitic fragments in some of the coarser clastics indicate that volcanic debris was supplied to the sediments. (4) Arkosic sediments with very scarce interbeds of sericite schist. (5) Sericite schist, practically without arkose interbeds, that probably represents a fine clastic rock such as shale or tuffaceous shale.

The stratigraphic relationship of these five members cannot be stated with certainty, owing to the lack of sufficient determinations of tops. It is suggested, though on insufficient data, that the greenstone mass (Fig. 2), assuming it represents flows, is older than the adjacent arkose-sericite schist complex; the rhyolite flow is clearly interbedded with this complex. The arkose-sericite schist member was intruded by rhyolite porphyry before the deposition of the Apache group. This intrusive porphyry, characterized by coarse quartz and albite phenocrysts, is not included in the Pinal schist.

The outcrop pattern suggests folds that trend

northeast; small-scale isoclinal folding with this trend was observed in the arkose-sericite schist member. Boudinage structure (Cloos, 1947) is apparent control over the folds and faults in the post-Pinal rocks in the Little Dragoon Mountains.

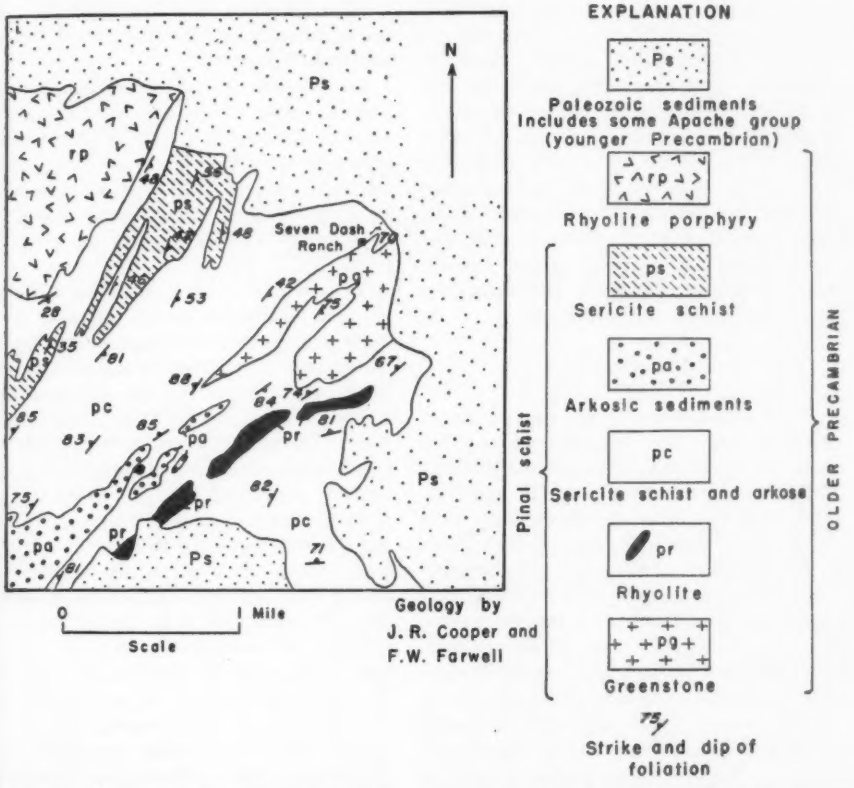

FIGURE 2—GENERALIZED MAP SHOWING SUBDIVISIONS OF PINAL SCHIST, LITTLE DRAGOON MOUNTAINS

very striking at many places in the arkosic sericite schist complex. The rhyolite flow also appears to have been severed into separate smaller masses. Except at the centers of large bodies of greenstone, rhyolite, and thick-bedded arkose, the rocks are well foliated, implying strong dynamic metamorphism. The foliation strikes essentially northeast; it may be axial-plane foliation. Metamorphism ranges from the chlorite to the amphibole grade.

Rocks of the Apache group (younger Precambrian) and Paleozoic sediments rest with angular unconformity on the Pinal schist. The older Precambrian structures have exerted no

BAGDAD AREA

General Statement

Bagdad is in west-central Arizona (Fig. 1) in the northwest part of a mountain region that is marked by more or less continuous exposures of Precambrian rocks, mostly granitic. Approximately 38 square miles in the Bagdad area were mapped on a scale of 1/12,000, between November 1943 and August 1945, by the writer, E. A. Scholz and J. D. Strobell, Jr., as a part of the copper investigations of the U. S. Geological Survey.

There is no positive evidence that the meta-

morphic and granitic rocks are of Precambrian age; the assumption is based on the general similarity in lithology and metamorphic structures to the Yavapai schist and Precambrian granitic rocks exposed in the Prescott-Jerome area to the east. In the Bagdad area, unmetamorphosed rhyolite tuff rests on an eroded surface of alaskite porphyry, one of the Precambrian intrusive rocks, and, by analogy to similar rocks elsewhere in Arizona, the tuff is probably late Cretaceous or early Tertiary in age. Younger than the rhyolite tuff are stocks of quartz monzonite, also presumably of late Cretaceous or early Tertiary age. The Precambrian and late Cretaceous or early Tertiary rocks are covered in part by late Tertiary or Pleistocene gravels and lava flows.

Yavapai Schist

The Yavapai schist in the Bagdad area is separated into three lithologic units: (1) a series of andesitic-basaltic flows and minor sedimentary interbeds; (2) rhyolitic and rhyolitic-andesitic tuffaceous sediments and shale interbeds; (3) shale, sandy shale, and sandstone.

The lavas in the volcanic unit have recrystallized to massive greenish-black amphibolites in which amygdaloid and pillow structures prove the volcanic character. The sedimentary interbeds have recrystallized to quartz-chlorite-sericite schist with or without garnet. The quartz content is appreciable and relict small-scale bedding and channeling prove the original sedimentary character. At one place, a 75-foot bed of agglomerate that contains unsorted volcanic fragments and bombs was recognized. Approximately 3,000 feet of this unit of volcanic and sedimentary rocks crops out, without the top or bottom being exposed.

The tuffaceous sediments have recrystallized to quartz-sericite schist, quartz-feldspar-biotite schist, and slate. The quartz-sericite schist contains coarse angular quartz and microperthite grains embedded in a matrix of abundant sericite, fine granular quartz, and alkalic feldspar. A pyroclastic origin is suggested by the angularity of the quartz grains, and intercalated conglomerate beds prove a sedimentary origin in part. The quartz-feldspar-biotite schist is poorly foliated and relict bedding is common. Locally, good graded bedding, channels, and cross-bedding aid in the determination of tops. Slate interbeds are 10 feet thick or more; presumably they represent original fine clastic rocks such as shale or tuffaceous shale. Approximately 2500 feet of tuffaceous sediments is present, but the base is not exposed.

The sedimentary rocks have been recrystallized to muscovite schist, quartz-muscovite schist, and muscovite quartzite. Except in the muscovite schist, bedding is easily recognized, and some determinations of tops can be made by graded bedding. Approximately 3,000 feet of sediments is present but the top is not exposed.

A transition zone from tuffaceous sediments to normal sediments is well exposed in the northwestern part of the Bagdad area (Fig. 3); the abundant determinations of tops to the east in this section prove that the tuffaceous sediments are older and grade into normal sediments. Unfortunately no section reveals the stratigraphic relationship of the tuffaceous sediments or the normal sediments to the volcanic rocks, as these volcanic rocks are separated from the sediments either by faults or by intrusive rocks. In the western part of the northern section of tuffaceous sediments, the quartz-sericite schist (rhyolite tuff) is in general similar to rhyolite tuff intercalated in the top (western part) of the volcanic rocks that are exposed in the southeastern corner of the Bagdad area. The biotite- and epidote-bearing albite in the quartz-feldspar-biotite schist may represent recrystallized andesitic or basaltic debris from the volcanic rocks. Solely on these data it may be inferred that the tuffaceous sediments accumulated after the outpouring of the andesitic-basaltic flows. If the inference is valid, the sedimentary rocks (mica schists) are the youngest rocks of the Yavapai schist in the Bagdad area.

Intrusive Rocks

The Yavapai schist was folded and faulted before the intrusion of a series of diverse rocks, part of which were guided along faults. Some intrusives form concordant bodies in the Yavapai schist and some are discordant.

The earliest of these intrusive rocks is rhyolite, limited largely to the southwestern part of the

FIGURE 3—GENERALIZED MAP OF BAGDAD AREA

area. Its texture is porphyritic with quartz phenocrysts, or nonporphyritic. Locally some foliation was noted.

Gabbro and related rocks, intrusive into the rhyolite, are widespread in the southern half of the Bagdad area. The gabbro ranges in texture from finely to coarsely granular, and in the western half of the area has a gneissoid foliation. Hornblende is the chief mafic mineral except near younger granite where biotite is common. Anorthosite dikes intrude coarse-grained gabbro, but fine-grained gabbro dikes cut the anorthosite. Spatially associated with the gabbro are smaller masses of quartz diorite, and a transitional boundary suggests a close genetic relation between the two rocks. Some dikes of diabase may be related genetically to the gabbro.

Large masses of alaskite porphyry intrude the gabbro in the western part of the area. Of several facies, the prevailing one contains quartz and feldspar phenocrysts in a finely crystalline groundmass.

Granodiorite gneiss crops out in small masses in the northern and eastern part of the area. The texture is granular, and the structure gneissoid from parallel flakes of biotite. The granodiorite gneiss intrudes the Yavapai schist and is definitely intruded by younger granite, but it has not been found in contact with the rhyolite or alaskite porphyry. The relations between the granodiorite gneiss and gabbro are not definite, but dikes of gneiss appear to cut the gabbro, suggesting a younger age for the gneiss.

The most widespread intrusive igneous rock in the Bagdad area is a porphyritic granite that contains orthoclase phenocrysts as much as 3 inches in length embedded in a medium-to coarse-grained groundmass of orthoclase, subordinate plagioclase, quartz, biotite, and muscovite. Some orthoclase phenocrysts were oriented by flowage. The granite intrudes all the units of the Yavapai schist, the gabbro, the alaskite porphyry, and the granodiorite gneiss, clearly proving its late age in reference to the other intrusive rocks. Aplite-pegmatite dikes, sills, and irregular masses cut the granite and older rocks near their margins with the granite.

Structure of the Yavapai Schist

The evidence for unraveling the stratigraphy and structure of the Yavapai schist is fragmentary due in part to the widespread occurrence of younger intrusive rocks. In the southern half of the area, a major syncline having an overturned western limb is suggested by the two belts of volcanic rocks, if the simplest structural interpretation is made concerning these two belts prior to faulting and igneous intrusion (Fig. 3). The northern outcrops of tuffaceous sediments and sediments indicate the western limb of a syncline, which may or may not be related to the syncline to the south.

A mile west-southwest of Bagdad, rhyolite (marked as intrusive rock on Fig. 3) separates the overturned volcanic rocks with northeast strike from the overturned tuffaceous sediments with north strike. This discordance in strike between volcanics and tuffaceous beds is interpreted as a result of faulting, prior to the intrusion of the rhyolite. An unconformity would give the same structural discordance. However, the tuffaceous sediments (quartz-feldspar-biotite facies) are high in the stratigraphic section in the northern exposures. Furthermore, the sedimentary rocks and tuffaceous sediments at the south margin of the map are in fault contact, as shown by structural discordance, but none of the usual features such as gouge or crushed rock are present. This fault, apparently of pre-metamorphic age, has the same trend as, and appears to be the southern extension of, the contact between volcanics and tuffaceous sediments to the north. Although this is not proof of a fault where the rhyolite was intruded, it lends support to that interpretation.

In the southeastern corner of the area, the volcanic rocks strike northeast (Fig. 3) and are separated from the adjacent sediments by intrusive rocks (diabase, gabbro, and granite). Southeast of the volcanics, the minor fold axes in the sedimentary rocks strike northwest, parallel to the strike of sedimentary beds on the northwest side of the volcanics. Clearly the sedimentary rocks were in fault contact with the volcanics, prior to the intrusion of the igneous rocks, and the masses of sediment may

have been connected prior to faulting. Unless a very complicated fold structure was present before the faulting that moved the sediments in juxtaposition to the volcanics, the two rock units must have been structurally discordant prior to faulting. The regularity of the trend of the volcanics does not suggest such a complicated fold, but no evidence is available to present a satisfactory explanation. However, it is clear that two essentially parallel faults, separating the volcanics and sediments, guided the younger diabase, gabbro, and granite intrusions.

In the southern half of the Bagdad area, the sedimentary rocks are acutely folded, in contrast to the more regular structural trends to the north. This acute folding may have resulted either from the application of orogenic stresses or from the forceful intrusion of the younger igneous rocks, or from both. In general, discordance exists between folded structures and igneous contacts. Furthermore, the sedimentary rocks are acutely folded in the southeastern-most exposures where igneous rocks are confined to the fault that separates the volcanics from the sediments. However, it cannot be denied that in the south-central part of the area, where the sediments were invaded repeatedly by magma, blocks of sediments may have been rotated and twisted during the magmatic cycle, even though folding by orogenic stresses may have preceded the igneous activity. The tuffaceous sediments cropping out less than a mile south of Bagdad are interpreted as appearing in the crest of a small anticline.

The evidence proves fairly conclusively the existence of folded structures with north to northeast trends, broken by faults prior to the intrusion of rhyolite, the first of a series of intrusions of rocks culminating in widespread granitic invasion. Only one period of orogeny is indicated, and it is presumed that the igneous rocks are related closely in time to this orogeny.

The westward-dipping fault in the southwest center of the area (Fig. 3) is younger than the granite, but is older than the Cretaceous (?) quartz monzonite (not separated on Fig. 3), which cuts across the fault. No evidence was found to date the fault as Precambrian, but in part it follows the course of the pre-rhyolite fault. To the north, a fault of similar trend and dip may have been connected with this fault before the intrusion of the Cretaceous (?) quartz monzonite. Later movement on the fault to the north has displaced late Tertiary lava flows.

Metamorphism

Thermal metamorphism has been intense adjacent to the granite. Muscovite flakes, 2 to 5 mm. in diameter, and sillimanite needles occur in the sediments (mica schists) in the south-central part of the area. The large muscovite flakes have a preferred orientation, in part parallel to bedding even where the beds are folded (magnitude of 50 to 500 feet). In this part of the area, the gabbro and related rocks rarely show foliation near the granite, and random coarse biotite crystals are common.

Evidence of dynamic metamorphism is best displayed in the western half of the area where the rhyolite and alaskite porphyry are locally foliated essentially parallel to the more pronounced foliation in the gabbro. Foliation in the volcanics is parallel to that in adjacent intrusive rocks. Local foliation in the granite is parallel to foliation in the adjacent gabbro. In the northern exposures of tuffaceous sediments, foliation is essentially parallel to bedding, but in the adjacent sedimentary rocks, foliation cuts across the crests of minor folds. In the southeastern belt of volcanics, foliation is poorly developed except for local bands parallel to or discordant with bedding (Fig. 3).

The slate in the tuffaceous sediments suggests low-grade metamorphism locally. An intermediate grade is suggested for most of the metamorphic rocks because of the biotite, hornblende, garnet, and calcic character of much of the plagioclase. The sillimanite zone, the highest grade, is locally present adjacent to the granite.

Prescott-Jerome Area

General Statement

The Prescott-Jerome area is in central Arizona (Fig. 1) at the southern margin of the Colorado Plateau. A current U. S. Geological Survey mapping project is covering two 15-minute quadrangles on a scale of 1/24,000. The

FIGURE 4—GENERALIZED MAP OF PART OF THE PRESCOTT-JEROME AREA

eastern quadrangle (Mingus Mountain) is being mapped by the writer and S. C. Creasey, and the western quadrangle (Prescott) is being mapped by M. H. Krieger and W. H. Eckstein. In addition, Creasey has done some mapping in adjacent quadrangles to the south. A generalized sketch map of part of the area mapped to 1949 is shown on Figure 4.

The Precambrian age of the Yavapai schist and intrusive rocks is demonstrated by remnants of unmetamorphosed Cambrian (?) sandstone and Devonian limestone resting on the older rocks. No younger Precambrian rocks (Apache group) have been found in this region and the correlation with the older Precambrian rocks is based on the general similarity in lithology and metamorphic structures to the Vishnu schist at the Grand Canyon and Pinal schist in the Globe area.

Younger than the Paleozoic sediments are late Tertiary lava flows and intercalated conglomerate, which in places rest directly on the Precambrian rocks, and elsewhere on the Paleozoic sediments. Quaternary alluvium conceals the Precambrian rocks in the western part of the area shown on Figure 4.

The type locality of the Yavapai schist (Jaggar and Palache, 1905) is in the Bradshaw Mountains (Bradshaw Mountains quadrangle, scale 1/125,000), partly shown on Figure 4 south of Latitude 34° 30′. Lindgren (1926) extended the Yavapai schist into the Jerome quadrangle (scale 1/125,000) to the north. Figure 4 covers much of the schist in the Jerome quadrangle.

As a result of the current mapping project, two broad units of the Yavapai schist have been recognized; they are separated by a profound north-trending fault. Paleozoic sediments cover the fault north of the map area proving the Precambrian age of the fault. For the purposes of this paper, the two units of the schist have been designated as the "foliated rocks" and the "nonfoliated rocks" respectively. No evidence has been found to suggest the age relations of these two units. The immediate problem is to emphasize the different structural pattern of the two units, which implies a different structural history.

FIGURE 4.—GENERALIZED MAP OF PART OF THE PRESCOTT-JEROME AREA

Yavapai Schist

Nonfoliated rocks.—The nonfoliated rocks, exposed in the eastern part of the area illustrated consist of andesitic pillow lavas, rhyolite and dacite flows and breccias, tuffaceous sediments, and coarse andesitic breccia, deposited in that order. In the area shown on Figure 4, foliation is weak or absent, but to the north, local schistose facies of some of these rocks are present. Relict structures, such as pillows, amygdules, flow breccia, and flow banding, are well preserved in the lava flows. Bedding, showing gradation in grain size, and channeling are equally well preserved in the sediments. Determination of tops of beds was easily done, attitudes of bedding were easily measured, and individual beds or flows were traced, so that the structure of the nonfoliated rocks was well determined.

The oldest of the nonfoliated rocks are the pillow andesites that crop out in the crest of a northwest-trending anticline in the northeast corner of the area (Fig. 4). The base is not exposed but over 3000 feet of andesite is present. The lavas are greenish-black and have a pilotaxitic texture of plagioclase and hornblende. Secondary epidote is locally present. Pillows range from 2 to 5 feet in their longest dimension, and have chilled selvages. Amygdaloidal facies are common.

Overlying the andesite are rhyolite and dacite flows that contain interbeds of breccia. The rhyolite is a gray flinty-appearing rock generally containing small quartz and albite phenocrysts. The dacite is a dark-gray lava with conspicuous plagioclase phenocrysts; quartz appears only in the groundmass. Flow banding is locally present in both silicic lavas. Part of the breccia may be flow breccia and part may be water-transported. Only one exposure of bedded material was found in the area covered by Figure 4, but 5 miles north sedimentary breccia and interbedded sandstone are intercalated with the rhyolite flows.

The tuffaceous sediments are separated into (1) beds of fine-grained crystal-tuff and interbedded chert; (2) coarse-grained tuffaceous sediments containing lithic fragments of andesite and rhyolite; and (3) jaspery iron ore beds, 2 to 20 feet thick. The iron ore beds, which appear throughout the stratigraphic section of tuffaceo-

ous sediments, make excellent markers for detailed structural studies. Approximately 6,000 feet of tuffaceous sediments is exposed. Intercalated dacite flows are prominent in the southern exposures of the tuffaceous sediments.

The andesitic breccia, interfingering with tuffaceous sediments at the base, appears in the trough of the southwestern syncline between the two faults in the north-central part of the area (Fig. 4). The fragments, ranging from 1 to 10 inches in largest dimension, consist almost entirely of porphyritic andesite that contains conspicuous plagioclase, pyroxene, and hornblende phenocrysts. At least 2000 feet of breccia is present, and the top is not exposed.

The nonfoliated rocks have been folded into a major anticline (northeast corner of Fig. 4) and into a major syncline (near southwestern margin of the nonfoliated rocks, Fig. 4). In addition, smaller anticlines and synclines occur on the flanks of the major folds. A fault trending north-northeast cuts the folded structures, offsetting the trace of the axial planes.

Small masses of gabbro have intruded the nonfoliated rocks. Southwest of the major syncline is a large mass of coarse-grained hornblende-biotite granodiorite, and its northeastern contact is essentially parallel to the major syncline. Medium-grained biotite-quartz diorite cuts across the folded structures of the Yavapai schist east of the nonfoliated rocks. Insufficient work has been done to establish the relations of the granodiorite to the quartz diorite. The granodiorite appears to be younger than the gabbro.

Foliated rocks.—The foliated rocks, exposed in the western part of the area shown on Figure 4, consist largely of volcanic flows and tuffaceous sediments, but include some clastic rocks of terrigenous source. The foliation of these rocks is not uniformly developed and some poorly foliated outcrops reveal relict textures and structures. Most of the rocks have been metamorphosed to slate and schist; many of the primary structures were destroyed, and those remaining are largely invisible except on water-polished outcrops in creek bottoms. Only in creek beds or in scattered favorable exposures on valley slopes, can determinations of tops be made with some degree of assurance, by using graded bedding and channeling as criteria. In some exposures of foliated rock, intersection of cleavage and bedding have been helpful in determination of tops, where the foliation is known to be parallel to the axial planes of the folds. On limbs of folds, foliation is so nearly parallel to bedding that discordances are difficult to recognize. Reliable determinations of the directions that the beds face, however, are too few in number and too scattered in distribution to determine the stratigraphic position of the various lithologic units that have been mapped.

Two litholigic units are sufficiently distinct in their characters as to be certain of their repetition or lack of repetition in the section. One of these is the purple slate and associated rocks that are lithologically similar to Wilson's (1939) Alder series occurring in the Mazatzal Mountains to the southeast (Fig. 1). This rock assemblage consists of purple to gray slate with interbeds of rhyolite tuff, pebble conglomerate containing numerous jasper and rhyolitic pebbles, and beds of limestone 1 to 10 feet thick. The limestone is limited to the eastern exposures of the purple slate unit and rhyolitic tuff is more abundant to the west. Small folds with magnitude ranging from 100 to 800 feet were mapped in this unit, using pebble conglomerate beds and limestone as markers. The thickness of these rocks is uncertain because of the numerous folds and thickening and thinning of beds owing to plastic deformation.

The other distinct lithologic unit for local correlation is volcanic breccia (Fig. 4) which contains coarsely porphyritic andesitic and subordinate rhyolitic fragments. The plagioclase phenocrysts of the porphyritic andesite are largely equant and tend to form clusters; the groundmass is light gray. Interbeds of tuffaceous sedimentary rock contain plagioclase crystal grains ranging in size from fine to coarse, and in some exposures, the graded bedding is clear. The southwestern exposures of breccia are not strongly foliated. Relict structures are common in the southern part of the eastern breccia belt which becomes more intensely foliated to the north. The breccia unit is probably between 3000 and 4000 feet thick.

A thick series of andesitic flows and tuffs is exposed along the southern margin of the area (Fig. 4), between the two belts of volcanic breccia. Pillow structures are rare in the lavas,

but they may have been destroyed at some places by dynamic metamorphism, for the rocks are schistose in this area. Relict quartz amygdules aid in separating flows from tuff. To the north, this thick section of andesitic rocks is covered by alluvium. In the northern exposures east of the volcanic breccia, an appreciable thickness of andesitic tuffs is present, but no lava flows were recognized except to the west of the volcanic breccia. No accurate measure of the thickness of the andesitic flows and tuffs can be given as it is possible that there is appreciable duplication in the section. Presumably at least 4000 to 6000 feet of lavas and tuffs represent the minimum thickness.

Alternating bands of rhyolitic and andesitic flows and tuffs, aggregating perhaps 5000 feet in thickness are exposed west of the westernmost exposures of volcanic breccia. In the southwestern exposures (Fig. 4), relict structures are destroyed by intense foliation, although small folds were mapped by using marker beds. In the northern exposures, relict flow banding in the rhyolite and amygdules in the andesite are well preserved.

The repetition of the volcanic breccia in the southern part of the area suggests a fold, but the absence of the purple slate to the west eliminates this simple explanation. The purple slate unit, however, is structurally discordant to the adjacent rocks, for individual beds in the adjacent rocks, both east and west, strike into the purple slate contact, implying that both contacts of the purple slate unit are faults. Possibly the purple slate unit represent the crest of a piercement fold.

Most of the reliable determinations of the tops of beds indicate that many of the beds face west, except in the recognizable folds of small magnitude. East-facing beds were recognized in the andesitic tuffs west of the purple slate in the north-central part of the area. Doubtful east-facing beds were observed in the eastern margin of the southwestern exposures of the volcanic breccia. But no major folds can be recognized by tracing a major unit from one limb of a fold to the other, perhaps because ol the cover of alluvium. The fact that most of the determinations of tops face west may mean that during large scale isoclinal folding, the eastern-facing limbs of the major folds may have been sheared out, or that fortuitously chiefly west-facing beds have been observed. Another possibility is that faulting duplicated units of an essentially homoclinal block in which the beds face westward except in small folds. Only by mapping southward where the foliated rocks are exposed over wide areas is it possible to assemble more pertinent data to answer these questions.

Granodiorite and gabbro are intrusive into the foliated rocks. Locally these intrusive rocks are schistose or gneissoid, parallel to the foliation in the adjacent Yavapai schist. The northeast-trending fault (southwest corner of Fig. 4) marks a structural discordance in rock types and foliation.

Relation of foliated and nonfoliated rocks.—Lausen (1930) limited the Yavapai schist to the western foliated rocks, concluding that it consisted of only metasediments. The nonfoliated rocks, or "greenstone complex" as he termed it, consisted of metavolcanic rocks, separated from the Yavapai schist (metasediments) by an angular unconformity. Wilson (1939) pointed out that a fault relationship exists between the two, a conclusion proved by detailed mapping (Fig. 4). The present study also has shown the presence of so many volcanic rocks in the foliated unit that it would be futile to limit the term "Yavapai schist" to metasediments. Furthermore, tuffaceous sediments are important constituents of the nonfoliated rocks.

The steeply west-dipping fault that separates the two broad units of the Yavapai schist extends southward, marking the boundary of the foliated rocks and granodiorite. Along this contact, no hornfels is present and the granodiorite is sheared and altered; this fact implies that the movement is post-granodiorite.

Until the two broad units of the Yavapai schist are found in normal stratigraphic position, their age relationship must remain in doubt. The fact that most of the western unit is foliated cannot be used as evidence that it is older because locally the western unit is nonfoliated, and locally the eastern unit is foliated.

West of the north-trending Precambrian fault, two faults, parallel to the Precambrian fault, displace Tertiary lavas, suggesting that the older Precambrian fault may have had some control over later faulting.

Metamorphism.—Metamorphism is largely low grade, corresponding to the chlorite zone, although locally some amphibole appears at the expense of chlorite in the metamorphosed andesite. Adjacent to the granodiorite, the tuffaceous sediments of the nonfoliated unit have been converted to hornfels.

Mazatzal Mountains

General Statement

Wilson (1939) made a significant contribution to Arizona Precambrian geology when he demonstrated that the Yavapai schist could be separated into stratigraphic units, as a guide for structural interpretation. Much of his work centered in the Mazatzal Mountains which culminate in Mazatzal Peak (Fig. 1). He also recognized other Precambrian rocks that are younger than the Yavapai schist but older than the Apache group.

Yavapai Schist

Wilson (1939, p. 1120–23) divided the Yavapai schist into three units designated as the Yaeger greenstone, the Red Rock rhyolite, and the Alder series. He proposed that "Yavapai group" embracing these three units be substituted for "Yavapai schist". This proposal has some merit, but the problem of stratigraphic nomenclature will not be discussed here.

The Yaeger greenstone, considered by Wilson to be probably the oldest member of the Yavapai, consists of intermediate to mafic flows, tuff, and agglomerate, with some sedimentary material. The type section was given as Yaeger Canyon in the Jerome area (a mile north of Fig. 4) and included all but the rhyolite of the nonfoliated unit. According to Wilson, the Yaeger greenstone crops out also in the Mazatzal Mountains and in the Tonto Basin east of Mazatzal Mountains.

The Red Rock rhyolite consists of flows and minor amounts of agglomerate, breccia, and intrusives of rhyolitic composition, and the type locality was selected as Red Rock Butte in the Mazatzal Mountains. The rhyolite in the "rhyolite and andesite flows" unit (Fig. 4) also was referred to the Red Rock rhyolite. Wilson stated that the Red Rock rhyolite was in fault contact with the Yaeger greenstone, but because he found fragments of greenstone in the rhyolite, he suggested the younger age of the rhyolite.

The Alder series, named from Alder Creek in the Mazatzal Mountains, is in fault contact with the Yaeger greenstone and the Red Rock rhyolite and consists of shale, grit, quartzite, and conglomerate. Wilson noted the same lithology also in the sediments (purple slate unit, Fig. 4) in the Jerome area. The character of the rhyolite pebbles in the conglomerate members suggested to Wilson that the Alder series was younger than the Red Rock rhyolite.

Mazatzal Quartzite and Related Rocks

Younger than the Yavapai schist are quartzites and shales, found largely in the Mazatzal Mountains. The oldest of them, 90 to 800 feet thick, Wilson termed the Deadman quartzite. It rests on his Red Rock rhyolite which is extensively oxidized to a depth of 100 feet, indicating a period of weathering between the accumulation of these two rocks. Overlying the Deadman quartzite with apparent conformity is a unit he named the Maverick shale, 500 to 800 feet thick. In the Mazatzal Mountains, the Mazatzal quartzite, which as a maximum thickness of 3800 feet, rests with apparent conformity on the Maverick shale. Twenty miles north of Mazatzal Peak, the Deadman quartzite and Maverick shale are missing and the Mazatzal quartzite rests on Red Rock rhyolite. At this place, the base of the Mazatzal quartzite has 300 feet of conglomerate containing some fragments of Red Rock rhyolite. Wilson (1939, 1147) states that the Mazatzal quartzite rests on an eroded surface of the rhyolite. A 75-foot layer of rhyolite is interbedded with the Mazatzal quartzite 500 feet above the base.

Wilson (1939, p. 1161) inferred that, after deposition of the rocks which are now the Yavapai schist, the region was uplifted and locally stripped of the Alder series, so the Deadman or Mazatzal quartzite was deposited on an eroded surface of the Red Rock rhyolite. The writer, without denying the existence of an erosion surface at the base of the Deadman or Mazatzal quartzite, finds that the evidence is weak in support of widespread uplift and erosion

after the deposition of the Yavapai schist. The work in the Prescott-Jerome area has shown the existence of at least two periods of rhyolite flow accumulation, and the stratigraphic relations in the nonfoliated rocks show that the rhyolite, which Wilson (1939, p. 1157) states can be reasonably correlated with his Red Rock rhyolite, is actually older than the tuffaceous sediments (Fig. 4) which are part of Wilson's Yaeger greenstone. Without wishing to detract from the value of Wilson's work, the writer believes that correlations based on lithologic similarity are dangerous, and, unless age relations can be established by superposition of rocks, some doubt will exist as to the validity of suggested correlations. Furthermore Wilson did not have adequate data to establish the age relations of his Alder series and Red Rock rhyolite; it is equally possible that the Red Rock rhyolite in the Mazatzal Mountains may be younger than the Alder series, and that no great amount of erosion necessarily preceded the deposition of the Deadman or Mazatzal quartzite. To the writer, the evidence of a rhyolite flow interbedded in the Mazatzal quartzite (Wilson, 1939, 1147) is equally good evidence of a very minor period of erosion. From the evidence available, serious doubt can be entertained as to the importance of this unconformity.

Structure

The low-angle, southeast-dipping thrust faults which involve the Deadman quartzite, Maverick shale, and Mazatzal quartzite Wilson, 1939, pl. 10), have not been recognized elsewhere in Arizona. Possibly the competence of the quartzites has been a factor in the formation of these thrust faults, and in other areas the rocks have yielded by folding.

One of Wilson's most important contributions is the proof that, in the Mazatzal Mountains, the Mazatzal quartzite was folded and faulted prior to the intrusion of granite (Wilson, 1939, p. 1143), dating the orogeny and granite intrusion as post-Mazatzal. The folds in the Yavapai schist and Mazatzal quartzite trend north to northeast (1939, p. 1131). In places, the folds are sharp, having overturned limbs; in other places, particularly where competent rocks are involved, the folds are more open.

Summary

The repetitious character and lenticularity of the andesitic and rhyolitic flows, tuffs, and tuffaceous sediments in the older Precambrian rocks introduces danger in any attempts of distant correlation. Possibly such distinct rock assemblages as Wilson's Alder series can be correlated with some assurance, and unusual textural assemblages, as in the one unit of volcanic breccia in the Jerome area, can be used for correlation over short distances. The only certain way of determining age relations between rock units is by normal stratigraphic methods (superposition of beds) which calls for detailed mapping and observation for determining the tops of beds. Because fault contacts are common, some doubt as to age relations may remain after detailed mapping. Further, unless distant correlations of rock units can be made, the correlation of structural events will be uncertain.

It is possible to make some general statements that provide a basis for regional interpretations. Clearly, the older Precambrian rocks have been folded in the Little Dragoon Mountains, Mazatzal Mountains, Bagdad, and Prescott-Jerome areas. The trend of the folds is northwest, north, or northeast, indicating general east-west compressive forces during the orogeny. In the Mazatzal Mountains, low-angle, southeast-dipping thrust faults are present, compatible with same general stress plan. High-angle faults also are present, with the same general trends as the folds. At Bagdad, some of these faults antedate the intrusion of the igneous rocks. In the Prescott-Jerome area, some faults are younger and others are older than the intrusive rocks. At Bagdad and in the Prescott-Jerome area, later movement has occurred along or parallel to the Precambrian faults, which suggests that some of the Precambrian structures have in part determined the trend of later faults.

In the four areas where sufficient detailed work has been done to give certainty to the conclusions, only one period of orogeny is clearly demonstrated. In the Little Dragoon and Mazatzal Mountains, the orogeny is pre-Apache (younger Precambrian), whereas in the Prescott-Jerome area, the orogeny can be dated

only as pre-Paleozoic; at Bagdad, no evidence is available for dating the orogeny. At the Grand Canyon, it has been established that a period of orogeny followed by the intrusion of granitic rocks was responsible for the deformation and metamorphism of the Vishnu schist; at this place the orogeny is older than the Grand Canyon series (younger Precambrian). The natural temptation is to assume that the orogenies in these five separate areas occurred at the same time, particularly because of the general parallelism of the folds where the trends were determined, and Wilson has termed this probable widespread orogenic disturbance, the Mazatzal Revolution. From a purely academic view, one might question this conclusion, for it is well known that the Precambrian covers an immense period of time, and it would be surprising if only one period of orogeny occurred in Arizona during the early Precambrian time. Hinds (1936) has suggested that two periods of orogeny and two periods of granitic invasion occurred in Arizona prior to the deposition of the younger Precambrian Grand Canyon series and Apache group, the Mazatzal quartzite marking the period of sedimentation between these orogenies. Because no positive angular unconformities have been found between the Mazatzal quartzite and Yavapai schist, some doubt exists regarding the validity of this older period of orogeny and granitic invasion. Until more precise correlations of the older Precambrian rocks in Arizona can be made, based on radioactivity or other methods, the simplest explanation is that only one period of orogeny, corresponding to Wilson's Mazatzal Revolution, has occurred in Arizona during early Precambrian time.

The degree of metamorphism of the older Precambrian rocks is varied. Rather intense dynamic metamorphism resulting in local boudinage structures is present in the Little Dragoon Mountains. In the Mazatzal Mountains, Wilson reports rather weak dynamic metamorphism except near granite contacts. In the Bagdad area, dynamic metamorphism was of only local importance, and thermal metamorphism related to the granite was strong. In the Prescott-Jerome area, dynamic metamorphism was intense in part of the area and very minor in the rest. Also thermal metamorphism is very local, suggesting perhaps that the granodiorite and quartz diorite are less effective than granite in thermal metamorphism. Certainly the intensity of metamorphism cannot be used as a valid criterion for regional correlations.

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Numbers show the location of places mentioned in the text

1 Andover, Andover Twp., Ashtabula Co., Ohio
2 Bartholomew Quarry, Hayfield Twp., Crawford Co., Pa.
3 Bedford, Bedford Twp., Cuyahoga Co., Ohio
4 Beech School, Woodcock Twp., Crawford Co., Pa.
5 Chagrin Falls, Chagrin Falls Twp., Cuyahoga Co., Ohio
6 Chardon, Chardon Twp., Geauga Co., Ohio
7 Cleveland, Cuyahoga Co., Ohio
8 Corry, Corry Twp., Erie Co., Pa.
9 Delamater School, Richmond Twp., Crawford Co. Pa.
10 Hungry Run, Union Twp., Erie Co., Pa.
11 Littles Corner, Hayfield Twp., Crawford Co., Pa.
12 Meadville, West Mead Twp., Crawford Co., Pa.
13 North Bristol, Bristol Twp., Trumbull Co., Ohio
14 Oil City, Cornplanter Twp., Venango Co., Pa.
15 Orangeville, Hartford Twp., Trumbull Co., Ohio
16 Pages Corners, Bloomfield Twp., Crawford Co., Pa.
17 Pennline, Conneaut Twp., Crawford Co., Pa.
18 Pinney School, Richmond Twp., Crawford Co., Pa.
19 Riceville, Bloomfield Twp., Crawford Co., Pa.
20 Rouseville, Cornplanter Twp., Venango Co., Pa.
21 Shellhammer Hollow, Woodcock Twp., Crawford Co., Pa.
22 Taylor Strand School, Athens Twp., Crawford Co., Pa.
23 Titusville, Oil Creek Twp., Crawford Co., Pa.
24 Warren, Warren Twp., Trumbull Co., Ohio
25 Wick, Wayne Twp., Ashtabula Co., Ohio

EXPLANATION

Outcrop of the Berea sandstone

Outcrop of the Bartholomew siltstone member

Location of rock exposure

Letters refer to location of sections on the line A-A' (see plate 2)

LAKE ERIE

LAKE
GEAUGA
CUYAHOGA
PORTAGE
ASHTABULA
TRUMBULL
MERCER

Euclid, East Cleveland, Cleveland, Mayfield, Chester, Munson, Claridon, Huntsburg, Willoughby, Kirtland, Chardon, Hambden, Montville, Perry, Painesville, Mentor, Concord, Leroy, Thompson, Madison, Harpersfield, Austinburg, Jefferson, Denmark, Pierpont, Trumbull, Morgan, Lenox, Dorset, Richmond, Harpersgrove, Rome, New Lyme, Cherry Valley, Andover, Windsor, Orwell, Colebrook, Wayne, Williamsfield, Warrensville, Orange, Russell, Newbury, Burton, Middlefield, Mesopotamia, Bloomfield, Greene, Gustavus, Kinsman, Brooklyn, Newburg, Parma, Independence, Bedford, Solon, Bainbridge, Auburn, Troy, Parkman, Farmington, Bristol, Mecca, Johnston, Vernon, Brecksville, Northfield, Macedonia, Twinsburg, Aurora, Montua, Hiram, Nelson, Southington, Champion, Bazetta, Fowler, Hartford, Hinckley, Richfield, Boston, Hudson, Streetsboro, Shalersville, Freedom, Windham, Braceville, Warren, Howland, Vienna, Brookfield

Conneaut, Summerhill, Pine, Summit, North Shenango, Sadsbury, South Shenango, East Fallowfield, Greenwood, Fairview, Hayfield, Woodcock, Vernon, West Mead, East Mead, Union, East Fairfield, Fairfield, Greene, Sugargrove, Salem, West Salem, Hempfield, Otter Creek, Sandy Creek, Deer Creek, French Creek, Perry, New Vernon, Mill Creek, Pymatuning, Delaware, Fairview, Lake, Sandy Lake, Hickory, Jefferson, Cool Spring, Jackson, Worth

Fair-view, McKean, Franklin, Washington, Cussewago, Venango, Cambridge

CLEVELAND, CHAGRIN FALLS, GARRETTSVILLE, BRISTOLVILLE, KINSMAN, SHENANGO, STONEBORO, EUCLID, MENTOR, CHARDON, JEFFERSON, ANDOVER, CONNEAUT, LINESVILLE, MEADVILLE, CAMBRIDGE SPRINGS

Grand River, Shenango River, West Fallowfield, Ohio, Pennsylvania

41°45' 81°45' 81°30' 81°15' 81°00' 80°45' 80°30' 80°15' 80°00' 42°00' 41°30' 41°15'

5 0 5 10 15 20 25 Miles
1951

OUTCROP MAP OF THE BEREA SANDSTONE, AND THE BARTHOLOMEW SILTSTONE MEMBER OF THE ORANGEVILLE SHALE

Outcrop of the Berea sandstone on the Cleveland and Euclid quadrangles adapted from Cushing et al (1931). Map drafted by L. E. Miller.

s show the location of places mentioned in the text

a Co., Ohio
xp., Crawford Co., Pa.
Co., Ohio
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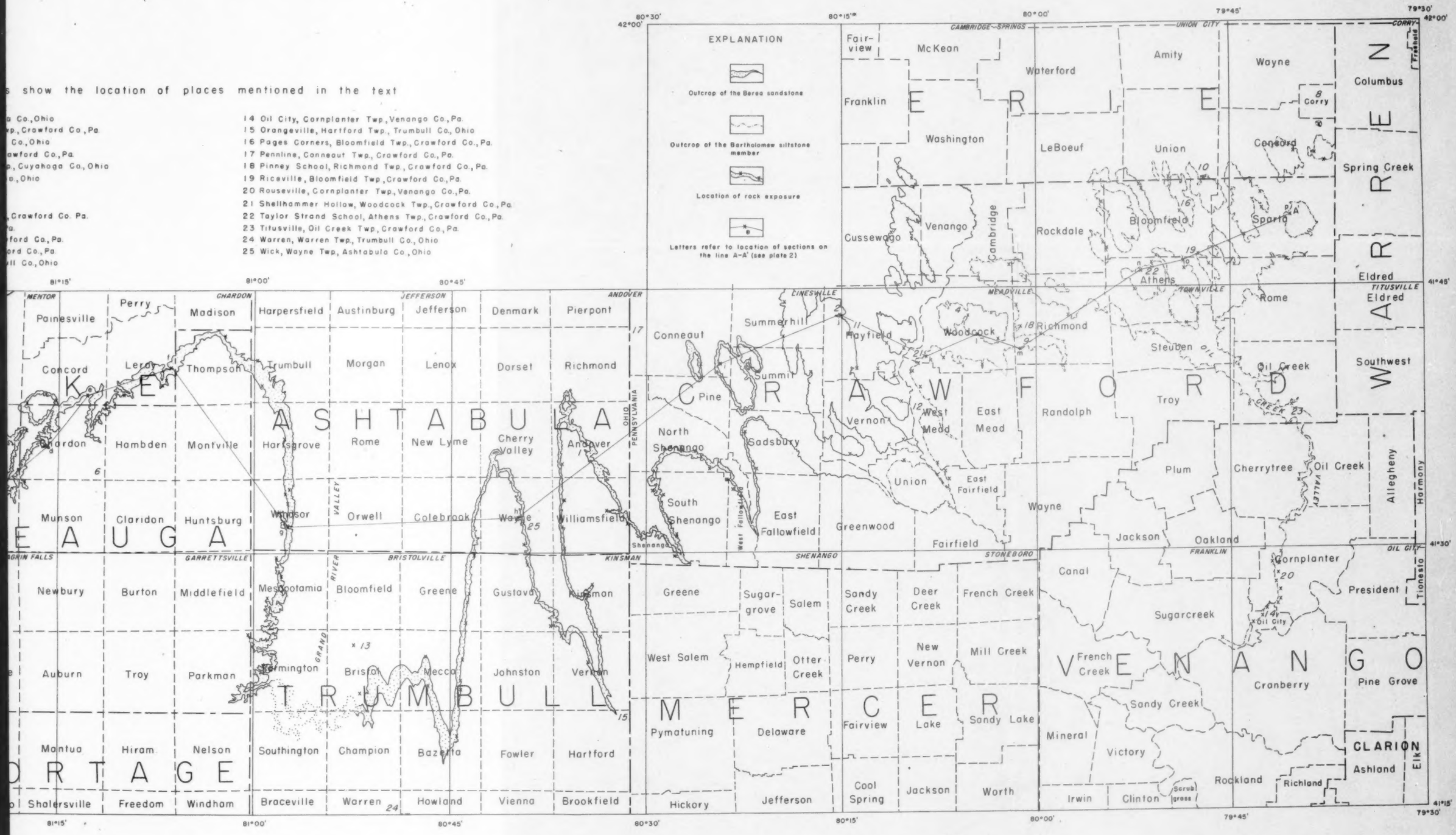
a., Cuyahoga Co., Ohio
o., Ohio

, Crawford Co. Pa.
a.
fford Co., Pa.
ord Co., Pa.
ll Co., Ohio

14 Oil City, Cornplanter Twp., Venango Co., Pa.
15 Orangeville, Hartford Twp., Trumbull Co., Ohio
16 Pages Corners, Bloomfield Twp., Crawford Co., Pa.
17 Pennline, Conneaut Twp., Crawford Co., Pa.
18 Pinney School, Richmond Twp., Crawford Co., Pa.
19 Riceville, Bloomfield Twp., Crawford Co., Pa.
20 Rouseville, Cornplanter Twp., Venango Co., Pa.
21 Shellhammer Hollow, Woodcock Twp., Crawford Co., Pa.
22 Taylor Strand School, Athens Twp., Crawford Co., Pa.
23 Titusville, Oil Creek Twp., Crawford Co., Pa.
24 Warren, Warren Twp., Trumbull Co., Ohio
25 Wick, Wayne Twp., Ashtabula Co., Ohio



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STRATIGRAPHY OF THE BEREA SANDSTONE AND ASSOCIATED ROCKS IN NORTHEASTERN OHIO AND NORTHWESTERN PENNSYLVANIA

BY WALLACE DE WITT, JR.

ABSTRACT

This paper summarizes stratigraphic information obtained in a field study of Upper Devonian and lower Mississippian rocks of northeastern Ohio and northwestern Pennsylvania. The upper part of the Chagrin shale has been traced from northeastern Ohio into the Riceville shale in northwestern Pennsylvania. The Cleveland member of the Ohio shale has been traced from its type locality near Cleveland eastward into the Grand River valley in western Ashtabula County, Ohio, where the black shale of the Cleveland appears to grade laterally into the upper part of the gray Chagrin shale. The Bedford shale and the Berea sandstone have been traced eastward from northern Ohio to the vicinity of Meadville in central Crawford County, Pennsylvania. The Bedford shale is underlain by the Cleveland member of the Ohio shale west of the Grand River valley and by the Cussewago sandstone in extreme northeastern Ohio and in northwestern Pennsylvania east of Meadville. The Cussewago sandstone, which forms a good key bed, is not a part of the Berea sandstone as has been suggested previously by some geologists. The Cussewago sandstone was derived from a different source and deposited from a different direction than either the Berea sandstone or the Corry sandstone. In northwestern Pennsylvania, the Bedford shale was found to be the same as White's Cussewago shale and Chadwick's Hayfield shale. In the vicinity of Meadville, Pennsylvania, the Bedford shale and the Berea sandstone grade laterally into a thin unit of siltstones and intercalated shale, here named the Shellhammer Hollow formation. Farther east, near Riceville, Pennsylvania, the Shellhammer Hollow formation grades laterally eastward into the Corry sandstone. The Corry sandstone, therefore, can not be considered an eastern siltstone facies of the Berea sandstone as has been suggested previously, although it is a near temporal equivalent of the Berea sandstone. A very coarse-grained deltaic sandstone occurs above the stratigraphic horizon of the Corry sandstone in part of southeastern Erie County, Pennsylvania. This local sandstone is here named the Hungry Run sandstone member of the Orangeville shale. A thin siltstone, characterized by many short curved markings, is an excellent stratigraphic marker in the basal part of the Orangeville shale, above the Berea sandstone, the Shellhammer Hollow formation, and the Corry sandstone. This siltstone, here named the Bartholomew siltstone member, has been traced widely over southern Erie County, Crawford County, and northwestern Venango County, Pennsylvania.

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Introduction

This paper describes the stratigraphy of the Upper Devonian and lower Mississippian rocks of northeastern Ohio and northwestern Pennsylvania as presented in preliminary form in Chart 21 of the United States Geological Survey's oil and gas investigations series (de Witt, 1946). Some data gathered since the publication of the chart are included. Although most of the material here presented was obtained from the study of outcrops, some subsurface data have been included to clarify the interpretation of the regional stratigraphy where surface information is inconclusive.

Location of the Area

The area discussed (Fig. 1) extends from Cleveland, Ohio, eastward to Corry, Pennsylvania, covering parts of ten 15-minute quadrangles in Ohio and parts of twelve quadrangles in Pennsylvania. The mapped area includes parts of Cuyahoga, Lake, Geauga, Trumbull, and Ashtabula counties, Ohio, and parts of Crawford, Erie, and Venango counties, Pennsylvania.

Field Work

Most of the field work was done in the late summer and fall of 1944 and the summer and fall of 1945. The writer examined outcrops of the Upper Devonian and lower Mississippian rocks in northeastern Ohio and northwestern Pennsylvania. A map was made of the Berea sandstone and of the Bartholomew siltstone member which occurs in the basal part of the Orangeville shale in northwestern Pennsylvania (Pl. 1). Elevations of points at the top of the Berea sandstone and the Bartholomew siltstone member were determined by aneroid barometer, and nine sections were measured by plane table and telescopic alidade.

The outcrop study determined the eastern limit of the Berea sandstone, the relation of the Berea sandstone to the Corry sandstone in Pennsylvania, and the relation of the Bedford shale of Ohio to the Cussewago shale of Pennsylvania of White (1881). First results of the study were published in 1946 (de Witt).

Acknowledgments

The writer was assisted in the field for 2 months in 1945 by Mr. C. W. Merrels, 2nd. Mr. D. F. Demarest spent several weeks in the field with the writer in the fall of 1944 and again in the summer of 1945. The writer wishes to thank Mr. W. H. Monroe and Mr. J. F. Pepper of the United States Geological Survey for their helpful suggestions and criticism of the paper. Thanks are due Mrs. Gail M. Everhart and Mr. L. E. Miller for their assistance in preparing this paper.

Previous Work

The relation of the Berea sandstone and the Bedford shale in Ohio to White's (1881) Corry sandstone, Cussewago limestone, Cussewago shale, and Cussewago sandstone in Pennsylvania has been a subject of discussion for many years. Soon after White proposed his tentative correlation of these rocks, other geologists proposed different interpretations. Figure 2 shows some of the correlations that have been proposed for the lower Mississippian rocks in northeastern Ohio and northwestern Pennsylvania. Prosser (1912) and more recently Caster (1934) have discussed the history of these different correlations. The writer's correlations of the lower Mississippian rocks in this area are shown on Figure 3.

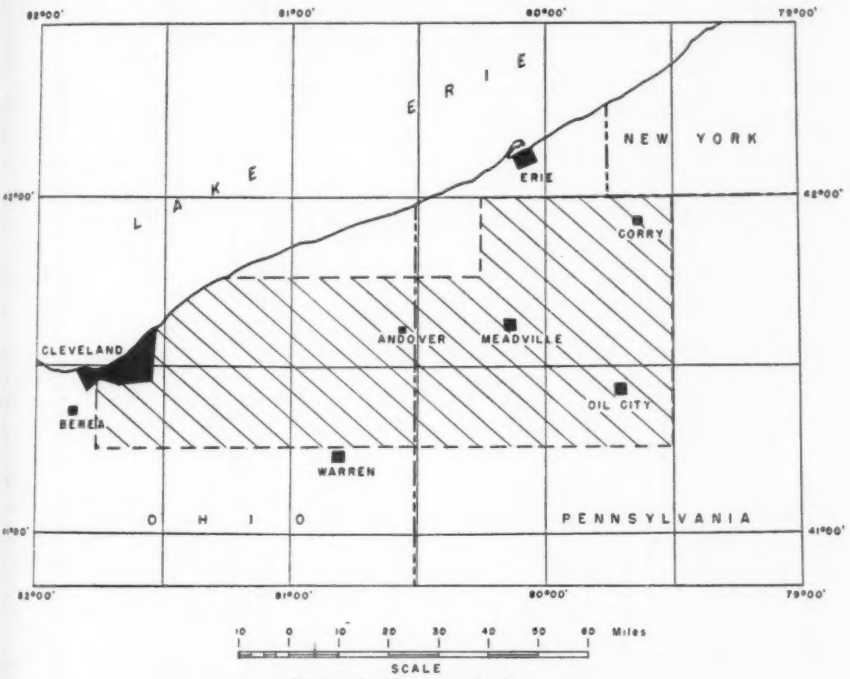

FIGURE 1.—LOCATION OF AREA

Devonian Rocks

Chagrin Shale

The Chagrin shale (Prosser, 1903, p. 521) is the oldest formation discussed in this report. In the vicinity of Cleveland, Ohio, the Chagrin is composed largely of soft gray shale and mudstone containing small limy nodules and some gray siltstones that range in thickness from half an inch to 3 inches. Although well records show the Chagrin to be about 500 feet thick in eastern Cuyahoga County, only 200 feet of the shale is exposed above the level of Lake Erie. Farther east, more of the formation is exposed, partly because the Chagrin thickens toward the east, and partly because of the southwest regional dip. In Ashtabula and Trumbull counties adjacent to the Ohio-Pennsylvania State line, about 1,200 feet of Chagrin shale is exposed.

Eastward throughout northern Ohio, the siltstones of the Chagrin shale increase in number and thickness; at many places the Chagrin contains groups of beds from 20 to 50 feet thick, composed largely of siltstones and interbedded silty mudrock. The siltstones range in thickness from half an inch to 16 inches and

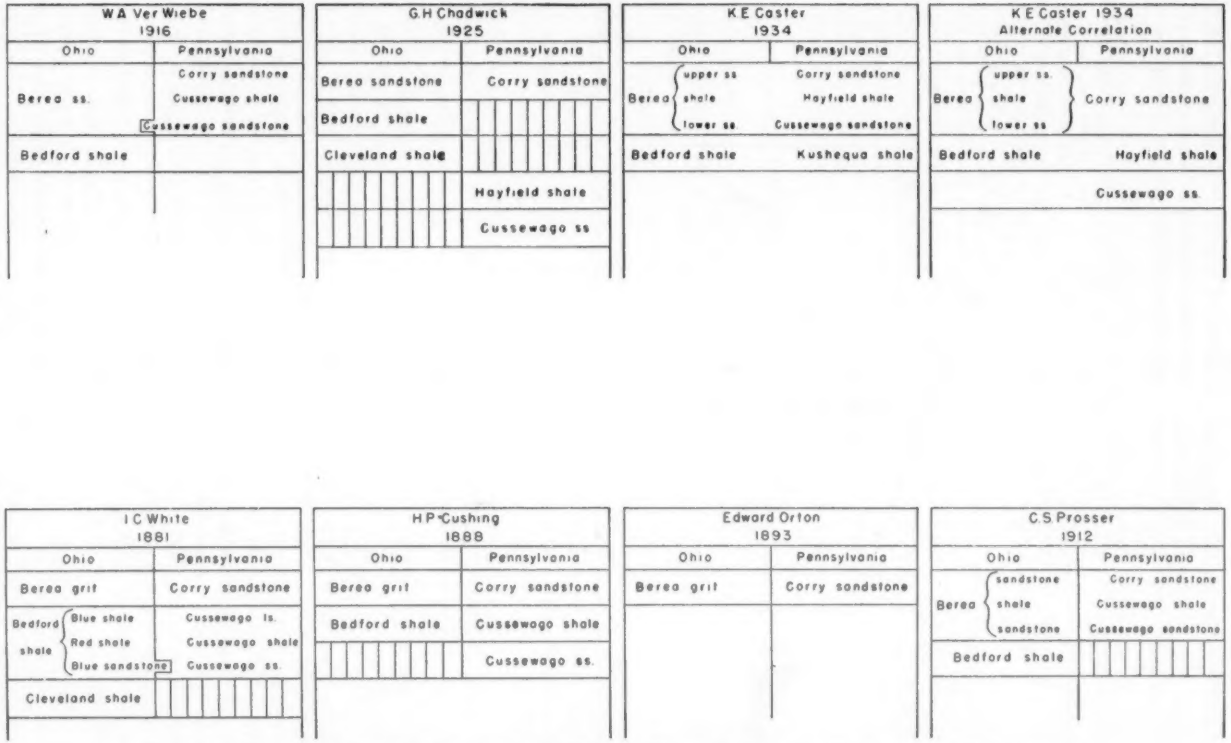

FIGURE 2.—PREVIOUSLY PROPOSED CORRELATIONS BETWEEN NORTHERN OHIO AND NORTHWESTERN PENNSYLVANIA

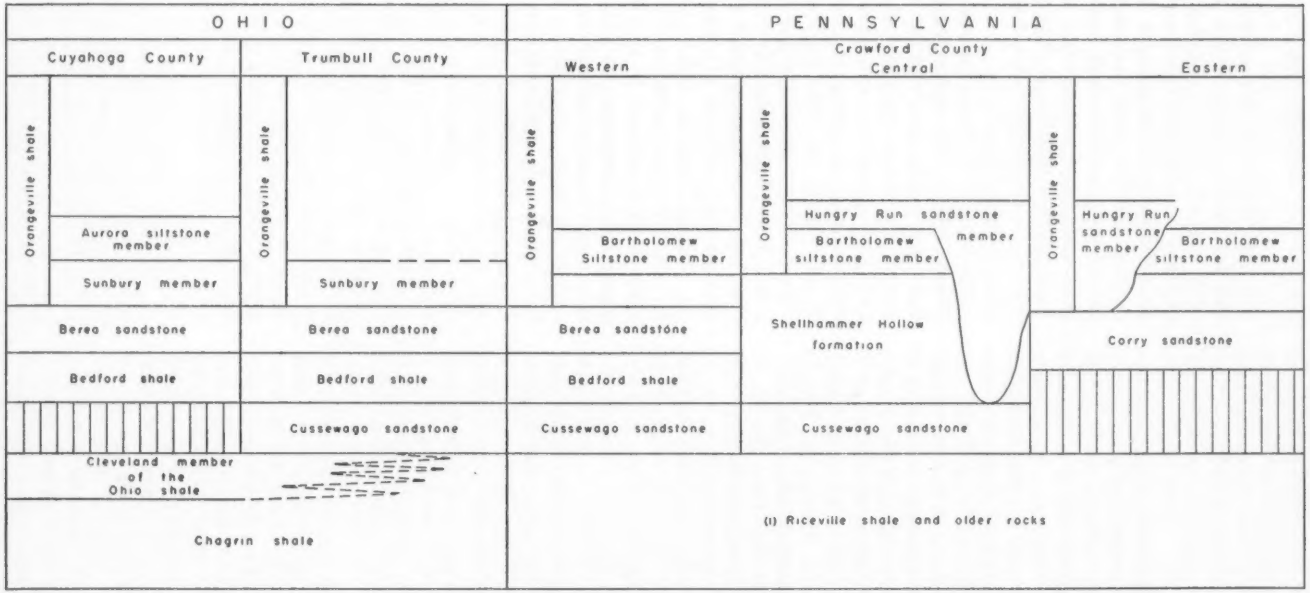

FIGURE 3.—CORRELATION OF ROCKS BETWEEN CLEVELAND, OHIO, AND CORRY, PENNSYLVANIA, AS PROPOSED IN THIS PAPER
(1) As originally defined by White (1881).

are fossiliferous at many places. The intercalated mudrock is generally unfossiliferous. The groups of beds of massive siltstones and interbedded silty mudrock in the Chagrin are separated by much thicker sequences of shale and silt-free mudrock.

In central and eastern Ashtabula County and northern Trumbull County, the upper beds of the Chagrin shale are made up predominantly of massively bedded white or gray siltstones and silty mudrock. The writer traced these siltstones eastward into western Crawford County, Pennsylvania, into rocks that were named Riceville by White (1881, p. 97–98).

The base of the Chagrin shale is not exposed in Ohio, but the top of the shale can be seen at many places. From the vicinity of Cleveland in eastern Cuyahoga County, into the valley of the Grand River in western Ashtabula County and western Trumbull County, the Chagrin shale is capped by the black shale of the Cleveland member of the Ohio shale (Pl. 2). At places in Cuyahoga County, the contact of the Chagrin and the Cleveland appears to be unconformable. In exposures in western Trumbull County and western Ashtabula County, the upper silty gray shales of the Chagrin appear to grade into the basal black shale of the Cleveland. In eastern Ashtabula County and eastern Trumbull County, the top of the Chagrin shale is not exposed, and the writer was unable to determine whether or not the Cleveland is present separating the Chagrin shale from the overlying Cussewago sandstone. Subsurface information from a well in the vicinity of Andover, Ohio, in southeastern Ashtabula County, indicates that a few feet of black shale of the Cleveland is present.

The Chagrin shale contains many fossils in northeastern Ohio, but the fauna of this shale has not been thoroughly studied and described. In eastern Ashtabula County, where long, well-exposed sections are not common, the following fossils in the Chagrin aid in distinguishing the massive siltstones in the upper part of the Chagrin from siltstones of similar appearance in the rocks of Mississippian age above:

Ambocoelia umbonata
Reticularia praematura
Spirifer disjunctus
Strophalosia sp?

Riceville Shale

In Crawford County, Pennsylvania, the Riceville shale (White, 1881, p. 97–98), which is the equivalent of the uppermost part of the Chagrin shale of eastern Ashtabula County, Ohio, is composed of interbedded gray silty shale; greenish-gray to tan, semi-fissile to massive mudrock; and white to tan, thin- to thick-bedded, fossiliferous siltstones, many of which are ripple-marked. These siltstones are so lenticular that individual lenses cannot be correlated between adjacent exposures.

The Riceville shale, as originally defined by White (1881, p. 97), where capped by the Cussewago sandstone is easily recognized throughout western and central Crawford County. In general the contact between the Riceville and the Cussewago is sharp. However, at a few places, as in the exposure near the abandoned Bartholomew quarry, 1 mile northwest of Littles Corner, Hayfield Township, the basal beds of the Cussewago sandstone contain some silt that may have been reworked from the Riceville. From the vicinity of Riceville, Bloomfield Township, eastward, the Cussewago sandstone is absent and the Riceville shale is capped by the Corry sandstone. There the contact appears to be conformable and is difficult to recognize, because the siltstones of the basal Corry at many places resemble those of the underlying upper Riceville.

Ohio Shale[1]

Cleveland member.—At its type locality in northeastern Cuyahoga County, the Cleveland (Newberry, 1870, p. 19, 21) consists of about 60 feet of tough bituminous black shale. The unweathered Cleveland is very massive and does not show fissility. On weathering, the shale develops fissility and breaks down into small flat chips having roughly circular outlines and very sharp edges. Most of these chips are coated

[1] In a forthcoming report on the stratigraphy, sedimentation, and paleogeography of sediments of Bedford and Berea age in the Appalachian Basin, to be published as a Professional Paper by the U. S. Geological Survey, the age relations of the Ohio shale and the Bedford shale are discussed. Two units, the Cleveland shale and the Huron shale, formerly treated as separate formations, are here considered as members of the Ohio shale because of their genetic relationship to that formation.

with iron oxides produced by the weathering of marcasite and pyrite in the shale.

The writer traced the black shale eastward across Lake and Geauga counties without difficulty, for the shale is easily recognized. It forms many cliffs along the small streams that trench the highlands of northern Geauga County. The Cleveland member of the Ohio shale retains its black color but thins eastward across Lake and Geauga counties, and is less than 20 feet thick in western Ashtabula County and western Trumbull County.

Along the west side of the Grand River valley, the Cleveland member begins to lose its characteristic black color by the admixture of much fine quartz silt. Thin lenses of quartz silt occur in the dark-gray or black shale. In this area the Cleveland ranges in thickness from 15 to 18 feet. Toward the east in central and eastern Ashtabula County and northeastern Trumbull County, the writer was unable to find exposures of the black shale because much of the area is mantled by glacial drift. Probably the Cleveland grades laterally into the upper beds of the Chagrin shale in the area where erosion has cut the Grand River valley.

The Cleveland member of the Ohio shale thins eastward to a feather edge west of the Ohio-Pennsylvania line. Prosser (1912, p. 389) reported a well drilled at Andover, Andover Township, Ashtabula County, Ohio, which penetrated some blackish shale capping a massive sandstone at a depth of 46 feet. This well was spudded in the lower part of the Bedford shale, and some of the quicksand reported above the blackish shale was undoubtedly the Cussewago sandstone. The massive sandstone when projected on the regional dip correlates with the upper beds of the Chagrin shale that crop out along the shore of Pymatuning Lake 2 miles east of Andover. From its stratigraphic position the blackish shale in this well could be the Cleveland member of the Ohio shale.

In general the contact at the base of the Cleveland member of the Ohio shale is sharply defined in the area between eastern Cuyahoga County and western Ashtabula County. Cushing (Cushing *et al.*, 1931, p. 39) has reported a slightly undulating contact at the base of the Cleveland member in the vicinity of Cleveland. In outcrops along the west side of the Grand River, western Ashtabula County, however, a transition zone occurs at the base of the Cleveland where thin stringers of black shale are intercalated in thin siltstones and gray mudrock. This transition zone indicates lateral gradation of the black shale of the Cleveland member into the gray shale and siltstone of the upper part of the Chagrin shale. The contact of the Cleveland with the overlying Bedford shale is not sharply marked at many places in Cuyahoga County. In western and central Cuyahoga County, the base of the Bedford shale is black or very dark gray and can be separated from the underlying black shale of the Cleveland member only by means of fossils. To the east in Lake and Ashtabula counties, the contact between the Cleveland member of the Ohio shale and the Bedford shale is more sharply defined.

Carboniferous (Mississippian) Rocks

Cussewago Sandstone

The Cussewago sandstone (White, 1881, p. 95–96), which is characteristically poorly lithified and friable, is composed of medium to coarse, angular to subangular quartz grains. An iron-oxide coating on the grains colors the sandstone a dull greenish-yellow. The lower half of the Cussewago is generally massive; the upper half contains some slabby beds from half an inch to 3 inches thick; and at most places the upper 2 to 3 feet of the Cussewago is a very massive bed. In many places, steep-angled cross-bedding occurs in the more massively bedded parts of the sandstone, whereas ripple marks of small amplitude cover the surface of the thinner-bedded part of the Cussewago. In many places, small discoidal pebbles occur either isolated or in small lenses in the basal part of the sandstone. These pebbles are mostly vein quartz, although some fragments of chert and igneous rock were found at two localities. Lenticular limestones, rarely as thick as 1 foot, are present in the thinner-bedded part of the sandstone in many outcrops. These limestone beds are local in extent, and the writer was unable to correlate them in adjacent outcrops. A bed of mud-cracked shaly sandstone about 2 inches thick occurs 11 feet below the top of the Cussewago in the section at Bartholomew

quarry, Hayfield Township, Crawford County. An 8-inch layer of sandstone containing clay galls is present in the Cussewago sandstone in an outcrop on Woodcock Creek, 1.15 miles north of Pinney School, Richmond Township, Crawford County. The presence of mud-cracks, clay galls, and steep-angle cross-bedding indicates that the Cussewago sandstone was deposited subaerially in part. The Cussewago sandstone appears to be unfossiliferous.

White (1881, p. 91–96) gave the name Cussewago to a group of rocks, including a shale and a local limestone as well as the sandstone, and designated no type exposure for them. The present writer (de Witt, 1946) restricted the name Cussewago to the sandstone and designated the outcrop near the abandoned Bartholomew quarry as the type outcrop. In this exposure, the Cussewago caps the Riceville shale and is overlain by 22 feet of Bedford shale.

A study of the Berea sandstone in western Pennsylvania showed (Demarest, 1946) that the Cussewago sandstone is the surface equivalent of the gas-producing Murrysville sand of western Pennsylvania, that the source area of this sand body lay to the southeast in northern Virginia, and that the sand thins toward the northwest away from the source area. The Cussewago sandstone of the outcrop in northeastern Ohio and northwestern Pennsylvania is only a small part of the large Cussewago (Murrysville) sand body (Fig. 4).

The writer traced the Cussewago sandstone from an outcrop on Baughman Creek at North Bristol, Bristol Township, Trumbull County, Ohio, eastward across northeastern Ohio and northwestern Pennsylvania to an outcrop eight-tenths of a mile west of Taylor Strand School, Athens Township, Crawford County, Pennsylvania. The thickest exposure of the Cussewago is near Wick, Wayne Township, Ashtabula County, Ohio, where 30 feet of coarse-grained Cussewago crops out. The base of the sandstone is not exposed in this section. The sandstone thins eastward, and only 11 feet of Cussewago is present in the easternmost exposure near Taylor Strand School. The Cussewago sandstone is exposed at many places in northeastern Ohio and northwestern Pennsylvania. Its distinctive lithologic features make it one of the best key beds in the area, although locally it may be confused with the lithologically similar Hungry Run sandstone member of the overlying Orangeville shale.

At some places, the upper contact of the Cussewago sandstone is sharply defined, but at other places this sandstone appears to be gradational into the Bedford shale. In the section at Wick, Ohio, a bed of flaggy sandstone 16 feet thick separates the typical Cussewago sandstone from the typical Bedford shale. These rocks resemble a mixture of both lithologies and may represent a vertical gradation. East of Meadville, Pennsylvania, where the Shellhammer Hollow formation caps the Cussewago, the upper boundary of the sandstone is sharply defined.

Bedford Shale

General description.—At its type locality on Tinkers Creek near Bedford, Bedford Township, Cuyahoga County, Ohio, the Bedford shale (Newberry, 1870, p. 21) is composed of about 85 feet of light-gray silty shale, many thin platy siltstones, and some hard discoidal limy nodules. A wedge of red shale, which is 25 feet thick in Independence Township and thins eastward to a feather edge on the Cuyahoga-Lake county line, is present in the upper part of the Bedford shale north of the type locality. In the vicinity of Cleveland, the basal few feet of the Bedford is very dark and locally contains many fossils. Although the fauna of the Bedford is not completely described, it has been discussed by Prosser (1912), Girty (1912), and Cushing *et al.* (1931, p. 43–45). In the eastern half of Cuyahoga County, the Bedford shale contains two members that are composed of massively bedded siltstones and some interbedded gray silty shale.

Sagamore siltstone member.—The Sagamore sandstone lentil (Prosser, 1912, p. 26, 86, 88) is here called the Sagamore siltstone member of the Bedford shale, because it is made up predominantly of quartzose siltstone containing a small amount of very fine sand and because of its unknown areal extent. It is the smaller of the two siltstone members of the Bedford shale and crops out along the east side of the Cuyahoga River valley south of Bedford, Ohio. The Sagamore siltstone member is composed of

FIGURE 4.—RELATIONSHIP OF THE BEREA, THE CORRY, AND THE CUSSEWAGO SANDSTONES IN EASTERN OHIO AND WESTERN PENNSYLVANIA

Stippling shows the area covered by the Shellhammer Hollow formation.

many thin to massively bedded gray siltstones from 4 to 20 inches thick, thickest in the middle part of the member and thinner in the upper and lower parts. The Sagamore siltstone member, which has a maximum thickness of about 20 feet, occurs 30 feet above the base of the Bedford shale and is underlain by silty gray shale containing many thin ripple-marked siltstones.

Euclid siltstone member.—The Euclid (Morse and Foerste, 1909, p. 166), the more extensive of the two siltstone members of the Bedford shale, is exposed at many places from Independence Township, Cuyahoga County, northeastward to Willoughby Township, Lake County, a distance of about 22 miles. Because the Euclid is of unknown areal extent and is composed predominantly of massive light bluish-gray coarse-grained siltstones and some very fine-grained sandstones in beds from 3 to 18 inches thick, it is here called the Euclid siltstone member. In general the Euclid member is more massively bedded than the Sagamore member. The siltstones of the Euclid are ripple-marked and cross-bedded at some places. A zone of flow rolls (de Witt, 1949) about 2 feet thick is present in the lower part of the Euclid at many places. The Euclid has a maximum thickness of about 20 feet (Cushing, *et al.*, 1931, p. 42) and is separated from the Cleveland member of the Ohio shale by a few feet of dark-gray and black shale and some thin siltstones.

Exposures of the Bedford shale east of Cuyahoga County.—The writer traced the Bedford shale eastward across Lake and Geauga counties, where it crops out in the cliffs below the more resistant Berea sandstone. The silt content of the Bedford shale increases eastward; in exposures along the west side of the Grand River in western Ashtabula County and western Trumbull County, the Bedford is made up of about equal amounts of silty shale, silty mudrock, and thin-bedded ripple-marked siltstones. Commonly the siltstone beds contain fucoids on their upper surface.

The Bedford shale thins from about 85 feet at its type locality on Tinkers Creek to about 45 feet in western Trumbull County. It is underlain with gradational contact by the black shale of the Cleveland member of the Ohio shale. The upper contact of the Bedford is very irregular in the area between Cuyahoga County and Trumbull County, for the Berea sandstone fills deep channels, which were scoured into and at some places through the Bedford shale.

The writer traced the Bedford shale eastward across Ashtabula and Trumbull counties, Ohio, and into the vicinity of Meadville, Crawford County, Pennsylvania. It retains its characteristic lithology and thins eastward. It is 44 feet thick near Wick, Ashtabula County, Ohio, and 22 feet thick at the Bartholomew quarry section, Hayfield Township, Crawford County. East of the Grand River, the Bedford shale is underlain by the Cussewago sandstone and is overlain by the siltstone facies of the Berea sandstone. As previously mentioned, the contact between the Cussewago and the Bedford is sharp at some places and appears gradational at other places. East of the Grand River valley, the upper contact of the Bedford shale is conformable.

In the vicinity of Meadville, Pennsylvania the Bedford shale and the overlying siltstones of the Berea sandstone grade laterally into the Shellhammer Hollow formation and lose their identity as individual formations.

In the Bartholomew section, Hayfield Township, White (1881, p. 204) reported 35 feet of Cussewago shale, including 2 feet of limestone near the top, between his Cussewago sandstone and his Corry sandstone. The present writer traced the Bedford shale into this outcrop, where it lies between the Cussewago sandstone and White's Corry. Because the name Bedford has priority, the present writer (de Witt, 1946) has recommended that the name Cussewago shale be dropped from the literature.

Chadwick (1923, p. 69) gave the name Hayfield to White's Cussewago shale and assigned a pre-Bedford age to the shale. He also gave the name Hayfield to White's Cussewago limestone which, he stated, occurs in some of the outcrops in northeastern Ohio. The sporadic occurrence of his Hayfield limestone in Ohio was, according to Chadwick, the result of post-Hayfield pre-Bedford erosion, which produced an unconformity that rises progressively to the east across northeastern Ohio and northwestern Pennsylvania (Fig. 5). The present writer's field mapping does not confirm the presence of

Chadwick's summit unconformity at the base of the Bedford shale. The shale that was named Hayfield by Chadwick is the Bedford shale of section j, Plate 2.

is finely laminated and shows cross-bedding at some places. Small flattened pebbles occur in the channel sandstone phase in south-central Cuyahoga County. Pyrite cementing the sand

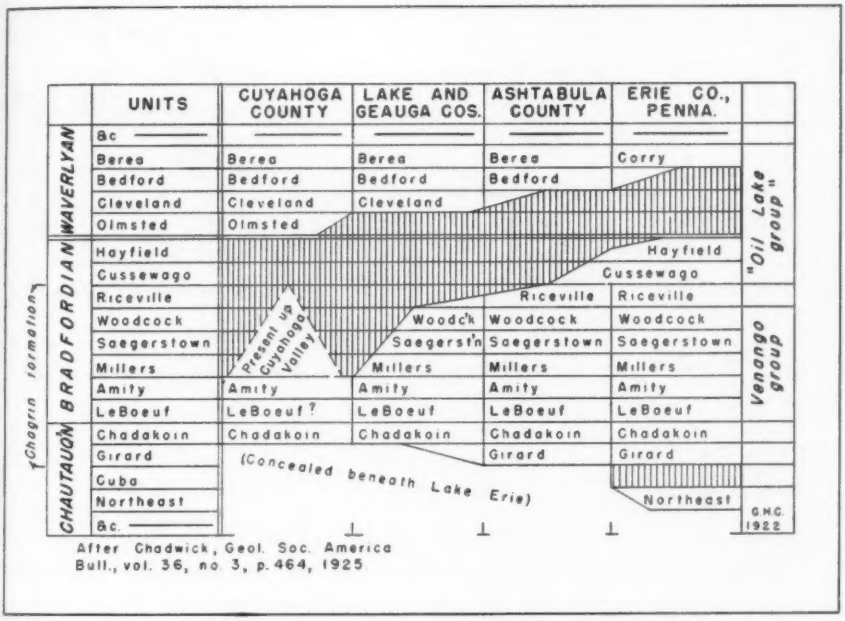

FIGURE 5.—CORRELATION OF THE CHAGRIN SHALE AND ADJACENT BEDS IN NORTHERN OHIO AND NORTHWESTERN PENNSYLVANIA, AS PROPOSED BY G. H. CHADWICK
Shows diagrammatically the position of his summit unconformity.

Berea Sandstone

A regional study of the Berea sandstone (Newberry, 1870, p. 21, 29) by the Appalachian Fuels Project (Pepper, Demarest, and de Witt, 1945; Demarest, 1946; de Witt and Demarest, 1947; de Witt, 1949) shows that the Berea in northern Ohio and northwestern Pennsylvania was derived from a northern source and deposited as a large delta, the subaerial part of which covered northern Ohio from Huron County to western Ashtabula County (Fig. 6).

The members of the Appalachian Fuels Project recognize three phases of Berea sandstone. The first and oldest phase is the massive, medium-grained sandstone which fills the channels that were scoured into and at some places through the Bedford shale. The sandstone grains occurs in the lower foot or two of some of the channel sandstones in Cuyahoga and Geauga counties. The channel sandstone of the Berea tends to disintegrate into aggregates of grains that give the appearance of a coarse-grained stone. Because of the similar appearance of the Cussewago sandstone and the coarse aggregates of grains found in the channel sandstone phase of the Berea, some geologists (Prosser, 1912, p. 396) concluded that the Cussewago was a part of the Berea. The two sandstones are, however, petrographically different, and were deposited from different directions (Fig. 4).

The second or fluviatile phase of the Berea sandstone lies above the channel sandstones in a sheet 20 to 35 feet thick and is characterized by much steep-angle fluviatile cross-bedding

and small-scale stream scour. This phase represents a deposit spread by streams across northern Ohio after the filling of the scour channels and prior to the inundation of the minute crystals, in aggregates of small cubic crystals, or as a cement bonding the quartz grains. This pyritic cap rock is found throughout the area of delta sandstone in northern Ohio.

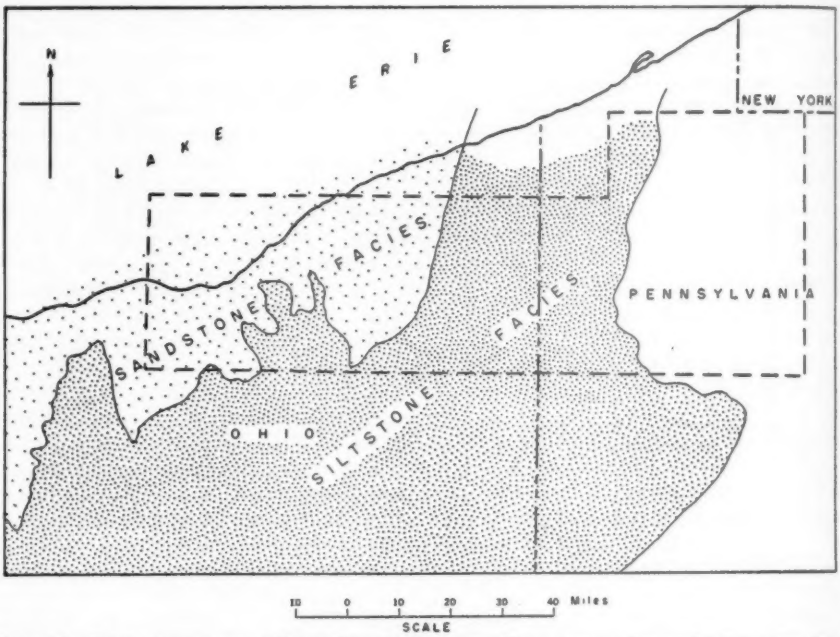

FIGURE 6.—RELATIONSHIP OF THE THICK DELTAIC SANDSTONE FACIES OF THE BEREA SANDSTONE IN CENTRAL NORTHERN OHIO TO THE THIN MARINE SILTSTONE FACIES IN NORTHEASTERN OHIO AND NORTHWESTERN PENNSYLVANIA
Dashed line shows area of this paper.

Berea delta by the sea. The fluviatile phase is thickest in western Cuyahoga County, thins to the east, and feathers out in the area of the valley of the Grand River in western Ashtabula County.

The third or marine phase of the Berea consists in this area of about 5 to 20 feet of thin-bedded, fine- to medium-grained sandstone that is ripple-marked throughout much of its extent. The ripple marks are mainly oscillation or interference types that apparently formed in the protected bays and estuaries adjacent to the retreating shore line of the Berea delta. This phase is thinnest near the center of the Berea delta in western Cuyahoga County and thickens to the east. The upper inch or two of the phase contains much pyrite in nodular masses of

Lenses of silty gray shale and very thin ripple-marked siltstone occur in many of the sections of the Berea sandstone in the delta area of northern Ohio. These lenses, from 2 to 15 feet thick, are local in extent and do not correlate in adjacent outcrops. Some geologists (Prosser, 1912; Caster, 1934, p. 163–164) have cited these local lenses of shale as evidence that the Berea of northern Ohio is a tripartite formation composed of two sandstone members separated by a shale member. The irregular occurrence of lenses of silty shale in the Berea sandstone (Fig. 7) does not support this hypothesis.

The present writer traced the Berea sandstone from the type locality eastward around the edge of the highland area of Geauga County

FIGURE 7.—SECTIONS OF THE BEREA SANDSTONE IN NORTHEASTERN OHIO
Shows the irregular occurrence of lenses of shale and siltstone in the Berea sandstone. Adapted from Prosser (1912).

and into the valley of the Grand River in western Ashtabula County and western Trumbull County. The sandstone is well exposed in many of the streams in this area and makes a very good unit for field mapping. It ranges in thickness from 40 to 80 feet, and is thickest where the channel sandstone phase is thickest. The combined thickness of the fluviatile and marine phases is about 40 feet.

In the broad drift-covered valley of the Grand River, the Berea sandstone changes markedly. It thins to about 25 feet, changes from a fine-grained sandstone to a siltstone, and becomes conformable on the underlying Bedford shale. Unfortunately the area in which most of these changes occur is covered with glacial drift. However, Demarest and the writer, using core drill records, traced the Berea across a drift-covered area in Southington and Champion Townships, Trumbull County, and observed the changes in the sedimentation of the Berea. Marked thinning of the Berea sand occurs also along the edge of the delta at many places in the subsurface in northern Ohio (de Witt, 1949). The decrease in thickness results from the disappearance of the channel sandstone phase and the fluviatile phase. The change in grain size from fine sand to silt occurs in the marine phase of the Berea. The disappearance of the unconformity at the base of the Berea is the most marked change that occurs in the area of the Grand River.

The writer traced the siltstone facies of the Berea sandstone across northeastern Ohio and northwestern Pennsylvania into the vicinity of Meadville in central Crawford County. Throughout most of this area, the Berea is composed of a series of gray, tan, or white, very hard, lenticular siltstones that are thick-bedded at the top of the formation and thinner-bedded near the base. Some very silty mudstone is present in the lower part of the Berea. At many places one or more lenses of hard steel-gray siliceous limestone occur in the base of the siltstone facies. These lenses of limestone, which rarely exceed 10 inches in thickness, are local in extent and cannot be correlated between widely separated sections

The siltstone facies of the Berea sandstone thins eastward from 15 feet at Wick, Ohio to 7 feet at the Bartholomew quarry section near Littles Corner, Pennsylvania. In the Bartholomew quarry section, the siltstone facies of the Berea was identified as the Corry sandstone by White (1881, p. 204). Much of the resulting confusion of correlations came from this identification. As shown in Plate 2, at the Bartholomew quarry section, the 7 feet of Berea is underlain by 22 feet of Bedford shale. The siltstone facies of the Berea thins rapidly across Hayfield Township and grades laterally into the Shellhammer Hollow formation in the vicinity of Meadville.

Prosser's interpretation of the section at Pennline, Conneaut Township, Crawford County, supported White's misidentification of the siltstone facies of the Berea in Pennsylvania and thus appeared to show that the Bedford shale was not present on the Ohio-Pennsylvania State line. Of the 5 feet of sandstone which he found at Pennline, Prosser (1912, p. 391–392) wrote:

> "... the lower 3 feet or more of which is very soft, greenish-buff in color, and composed of moderately coarse quartz grains with some flat quartz pebbles. The upper part is in thinner layers and harder; but is a quartz sandstone with the lithologic characters of the Berea. The lower portion is soft and massive with the lithologic appearance of the Cussewago sandstone.
>
> "... This seems to show that the Bedford formation and the Cleveland shale do not extend as far east as the Ohio-Pennsylvania State line."

The logical conclusions to be derived from this interpretation would be that a thin wedge of Berea sandstone feathered out in extreme western Crawford County and that White's Cussewago shale was not of Bedford age.

Demarest and the present writer examined the section at Pennline and concluded from the presence of the small quartz pebbles and the typical greenish color of the sandstone that all of the sandstone exposed at Pennline is Cussewago. Only the basal part of the Cussewago sandstone is present at Pennline (Fig. 8); the remainder of it as well as the Bedford shale and the siltstone facies of the Berea is carried above the hill top by the regional dip.

Throughout northern Ohio and northwestern Pennsylvania, the upper contact of the Berea sandstone is sharp, although it is overlain conformably by the Orangeville shale. In northern Ohio, the pyritic cap rock of the Berea grades upward in a distance of 2 inches into the basal

part of the Sunbury member of the Orangeville shale. In northwestern Pennsylvania, where the pyritic cap rock is absent and the Sunbury member of the Orangeville is not recognized, the black shale of the Orangeville is conformable on the siltstone facies of the Berea sandstone.

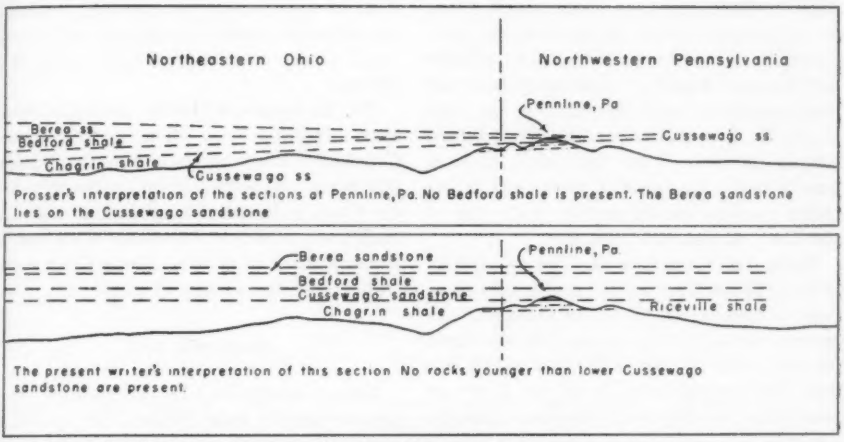
Northeastern Ohio
Northwestern Pennsylvania
Pennline, Pa
Berea ss
Bedford shale
Chagrin shale
Cussewago ss
Cussewago ss
Prosser's interpretation of the sections at Pennline, Pa. No Bedford shale is present. The Berea sandstone lies on the Cussewago sandstone
Berea sandstone
Bedford shale
Cussewago sandstone
Chagrin shale
Pennline, Pa
Riceville shale
The present writer's interpretation of this section. No rocks younger than lower Cussewago sandstone are present.

FIGURE 8.—SCHEMATIC DIAGRAMS SHOWING DIFFERENT INTERPRETATIONS OF THE SECTION AT PENNLINE, PENNSYLVANIA

The Berea sandstone is largely unfossiliferous. However, in the vicinity of the Ohio-Pennsylvania State line, the writer found a small fauna, composed largely of small pelecypods and brachiopods, in the upper part of the siltstone facies of the Berea sandstone. The writer did not study this fauna.

Corry Sandstone

The Corry sandstone (White, 1881, p. 92) in the vicinity of its type locality, the now abandoned Colegrove quarry 1 mile south of Corry, Pennsylvania, consists of about 20 feet of gray and white siltstone and some interbedded fine-grained sandstone. The Corry is massive-bedded near the top and thinner-bedded near the base. In general the individual beds are very lenticular; in long exposures, they feather out and their place is taken by a corresponding thickening of the adjacent beds. The basal part of the Corry is covered in the type area, but the entire formation is exposed at many places toward the southwest along Oil Creek. Here many thin lenses of gray siliceous limestone similar to those found in the siltstones of the Berea occur in the lower part of the Corry.

At many places in eastern Crawford County and northern Venango County, the Corry can be separated roughly into three units—a lower unit of massively bedded siltstones and fine-grained sandstones; a medial unit of thinner-bedded siltstones intercalated in silty mudrock and silty shale; and an upper unit of massive siltstones separated by some thin shaly partings (Cathcart *et al.*, 1938, p. 3; Dickey *et al.*, 1943, p. 20). This subdivision can be seen along State Route 8 and the cliffs bordering the Pennsylvania Railroad in the vicinity of Rouseville and Oil City. In these exposures, the medial unit of the Corry is made up mostly of silty mudrock and siltstone and little shale.

The writer traced the Corry sandstone westward from its type locality to the vicinity of Riceville, although much of this area is covered by glacial debris and outcrops are scarce. The formation thins from about 20 feet to about 6 feet. In the area between Riceville and Taylor Strand School 2 miles to the west, the Corry grades laterally into the Shellhammer Hollow formation and cannot be identified.

Throughout much of its outcrop, the Corry

sandstone lies on the Riceville shale and the contact appears conformable. In general the base of the Corry is sharply defined except in the northeastern part of Crawford County, where the basal siltstone of the Corry rests on the upper siltstone or silty mudstone of the Riceville shale. The upper contact of the Corry is not sharply defined in much of the area, especially in southeastern Crawford County and Venango County, where many fine- and medium-grained sandstones occur in the rocks above the Corry. However, the Bartholomew siltstone member of the Orangeville shale is present in the basal part of these rocks, which makes possible the delineation of the top of the Corry sandstone in this area.

Fossils are common in the Corry sandstone at many places. They are not readily seen, however, in fresh exposures of the sandstone and appear only after the material has weathered for some time. Caster (1934, p. 123–124) has discussed the paleontology of the Corry at some length and lists about 60 genera from this formation.

Shellhammer Hollow Formation

In the area between Meadville and Riceville a series of thin siltstones, silty mudstones, and shale occupies the stratigraphic position of the Bedford shale, Berea sandstone, and some basal Orangeville shale to the west and the stratigraphic position of the Corry sandstone and some basal Orangeville shale to the east (Pl. 2). This thin sequence of intercalated shaly and silty rocks is here named the Shellhammer Hollow formation. The type locality is 2 miles north of Meadville where the Meadville-Sagerstown road crosses Shellhammer Hollow. The Shellhammer Hollow formation is exposed on the road on each side of the hollow about 20 feet above the stream. This formation, called Zone A in Preliminary Chart 21 (de Witt, 1946), is everywhere capped by the Bartholomew siltstone member of the Orangeville shale and underlain by the massive Cussewago sandstone. The Shellhammer Hollow formation is 5 feet thick in an exposure eight-tenths of a mile south of Beech School, Woodcock Township, Crawford County, and thins into shale 4 inches thick in an exposure eight-tenths of a mile west of Delamater School, Richmond Township, Crawford County. East of this point the formation thickens, and in an exposure 1 mile west of Taylor Strand School, Athens Township, Crawford County, it is 2.1 feet thick. The Shellhammer Hollow formation is composed of about equal parts of siltstone, silty mudrock, and silty shale where it is thickest, and is composed almost completely of shale where it is thinnest.

The Shellhammer Hollow formation represents deposition in a shoal area in central Crawford County against which the Bedford and Berea sediments thinned on the west and the Corry sediment thinned on the east. The Shellhammer Hollow formation is present in the subsurface in eastern Mercer County and western Venango County (Fig. 4).

Orangeville Shale

General description.—In northeastern Ohio, the Orangeville shale (White, 1880, p. 63) is composed predominantly of very dark-gray to black shale containing small amounts of poorly bedded very dark-gray mudrock, some siltstone, and many limonitic nodules. Throughout much of its extent, the exposures of the Orangeville shale are stained yellow, orange, and brown by iron oxides. Its silt content increases eastward, and in northwestern Pennsylvania the Orangeville shale cannot be recognized as a separate unit.

In the vicinity of Cleveland, the Orangeville, as measured from the top of the Berea sandstone below to the base of the Sharpsville sandstone above, is about 125 feet thick. The Orangeville shale thins to the east as the basal sandstones and siltstones of the Sharpsville sandstone occur lower and lower in the section (Fig. 9). The Orangeville is about 80 feet thick near Warren, Ohio, and about 75 feet thick at Orangeville (White, 1880, p. 62), Hartford Township, Trumbull County, Ohio, the type occurrence of this shale. In Pennsylvania where an unnamed shale unit of the Orangeville lies between the Bartholomew siltstone member and the base of the Sharpsville sandstone, the present writer measured 42 feet of this unnamed shale unit at Shellhammer Hollow and 28 feet in the section 1 mile west of Taylor Strand

School in Athens Township, Crawford County. In southeastern Crawford County and western Venango County, the Orangeville shale and the overlying Sharpsville sandstone merge into a thick series of intercalated medium- and fine-

ville consists of very dark-gray and black shales and the local siltstones are absent. Therefore, the Sunbury shale is treated as the basal member of the Orangeville shale as far east as the typical zone of *Orbiculoidea herzeri* and *Lingula*

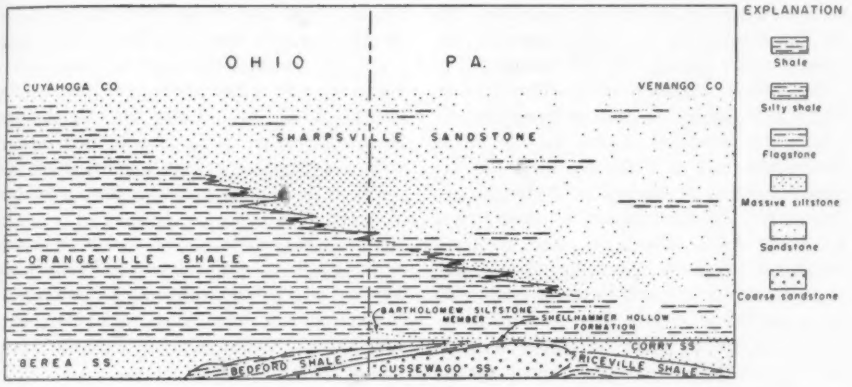

FIGURE 9.—DIAGRAMMATIC CROSS SCETION BETWEEN CUYAHOGA COUNTY, OHIO, AND VENANGO COUNTY PENNSYLVANIA

Shows the relationship of the Orangeville shale and the Sharpsville sandstone.

grained sandstones, siltstones, silty mudrock, and silty shale (Fig. 9). Locally some of the sandstones are conglomeratic.

The writer recognizes the following members of the Orangeville shale: the Sunbury member (de Witt, 1946), the Aurora siltstone member (Prosser, 1912, p. 123, 209, 211), the Chardon siltstone member (Prosser, 1912, p. 219–220, 229), the Bartholomew siltstone member, and the Hungry Run sandstone member.

Sunbur member.—In the vicinity of Cleveland, the Berea sandstone is overlain by about 6 feet of black shale, which is overlain by a local siltstone lentil. The basal 2 inches of the black shale contains many conodonts and two genera of inarticulate brachiopods, *Lingula melie* and *Orbiculoidea herzeri*. The writer found these fossils in the same stratigraphic position in the black Sunbury shale at the type locality in central Ohio. In central and eastern Cuyahoga County, where the Sunbury shale is separated from the Orangeville shale by local siltstones, the Sunbury shale can be regarded as a distinct formation. However, separation of the Sunbury from the Orangeville is impossible in much of northern Ohio, where the Orange-

melie can be found. This zone of fossils disappears from the section in the vicinity of Andover in eastern Ashtabula County, and the Sunbury member is not recognized across the State line in Pennsylvania.

Aurora siltstone member.—Four to six feet of massively bedded white siltstone caps the Sunbury member of the Orangeville shale in central and eastern Cuyahoga County. This siltstone, here designated the Aurora siltstone member, has a maximum thickness of about 6 feet on the outcrop and about 10 feet in the subsurface. It lies from 5 to 6 feet above the Berea sandstone along the Cuyahoga River south of Cleveland and is 15 feet above the Berea in the vicinity of Chagrin Falls in eastern Cuyahoga County.

Chardon siltstone member.—Eight feet of thin- to thick-bedded gray siltstones and intercalated silty shale occurs in the Orangeville shale about 30 feet above the Berea sandstone and is typically exposed in Stebbins Gulch near Chardon, in northwestern Geauga County. Prosser (1912, p. 220) named these rocks the Chardon sandstone member. Because the Chardon member is composed largely of coarse quartz silt, the

present writer here renames the member the Chardon siltstone member. Lithologically the Chardon member is very similar to the Aurora member. Recently Rothrock (1949, p. 1741) stated that the names Aurora and Chardon have been applied to different parts of a single unit. Although unable to trace the Aurora into the Chardon because of a lack of exposures, the present writer agrees with this interpretation.

Bartholomew siltstone member.—This member, which is composed of gray or brownish-gray siltstone, is present at or near the base of the Orangeville shale in Crawford, Erie, and Venango Counties, Pennsylvania. It averages less than a foot in thickness and is characterized by many short curved or curly markings, ranging in thickness from a film to an eighth of an inch and in length from one-quarter to three-quarters of an inch. In general the markings lie at random in the siltstone although at some places they are oriented roughly parallel to the bedding laminae. In an unweathered state, the markings are darker than the rest of the siltstone. Weathering etches away the soft material that composes these markings, imparting a peculiar worm-eaten look to the weathered siltstone. The markings make possible the positive identification of the Bartholomew siltstone member in both the weathered and unweathered state.

Because the characteristic curved marks resemble cuneiform writing, the writer first called this siltstone the graphic siltstone (de Witt, 1946). It is here proposed to name the siltstone the Bartholomew siltstone member of the Orangeville shale. The type exposure of the siltstone is in the Bartholomew section of White (1881, p. 204), where the Bartholomew siltstone member lies 8 feet above the top of the Berea, 15 feet above the top of the Bedford shale, and 37 feet above the top of the Cussewago sandstone.

The Bartholomew siltstone member, which forms an easily identified stratigraphic marker over a wide area in northwestern Pennsylvania, was traced by the writer from the vicinity of the Ohio-Pennsylvania State line eastward across Crawford and Erie counties into Warren County. The writer also traced the siltstone southward from Corry down Oil Creek to Oil City. Because of the many siltstones and sandstones that occur in the rocks above the Corry sandstone in the vicinity of Oil City, a careful search was required to locate the Bartholomew siltstone member.

The member occurs 15 feet above the siltstone facies of the Berea near the Ohio-Pennsylvania State line, 8 feet above the Berea at the Bartholomew quarry section, 2 feet above the Corry sandstone in sections near Corry, and from 1 to 3 feet above the Corry in the vicinity of Oil City. It caps the Shellhammer Hollow formation in the area between Meadville and Riceville except where erosion has removed both units in northeastern Steuben Township.

The Bartholomew siltstone member contains a few fossils at some places, including some *Lingula melie.* Two specimens of *Conularia* cf. *C. missouriensis* were found in an outcrop 1 mile north of Shaws, in East Fairfield Township, Crawford County.

Hungry Run sandstone member.—Ten feet of massive, iron-stained, coarse-grained sandstone and 2 feet of underlying massive siltstone are exposed in a small quarry on a headwater of Hungry Run 1 mile west of the southeastern corner of Union Township, Erie County, Pennsylvania. The 12 feet of rocks exposed in this quarry is here named the Hungry Run sandstone member of the Orangeville shale. The Hungry Run resembles the coarse-grained Cussewago sandstone but is better indurated. It contains much iron oxide, which stains the sandstone orange, purplish-brown, or deep reddish-brown. The sandstone is cross-bedded and the upper 2 feet is conglomeratic at the type locality. Many small lenses of flat discoidal pebbles, which range in diameter from one-half to two-thirds of an inch and in thickness from one-eighth to one-fourth of an inch, occur in the conglomerate. The pebbles are largely vein quartz, although a few pieces of chert, jasper, and igneous rock were found in the conglomerate. A 5-inch zone of clay galls and some very poorly preserved fossils occur 6 feet below the top of the sandstone at this locality. An 8-inch lens of petroliferous sandstone is present 1 foot below the zone of clay galls. The lower 4 feet of the member is finer-grained than the upper 6 feet. The sandstone grades down into massive siltstones.

The Hungry Run sandstone member extends southwestward from the type exposure in a belt about 5 miles wide and feathers out in the central part of eastern Crawford County (Fig. 10). Although the sandstone is rarely observed in place on the steep hill slopes, float blocks of the Hungry Run member can be found in small stream valleys.

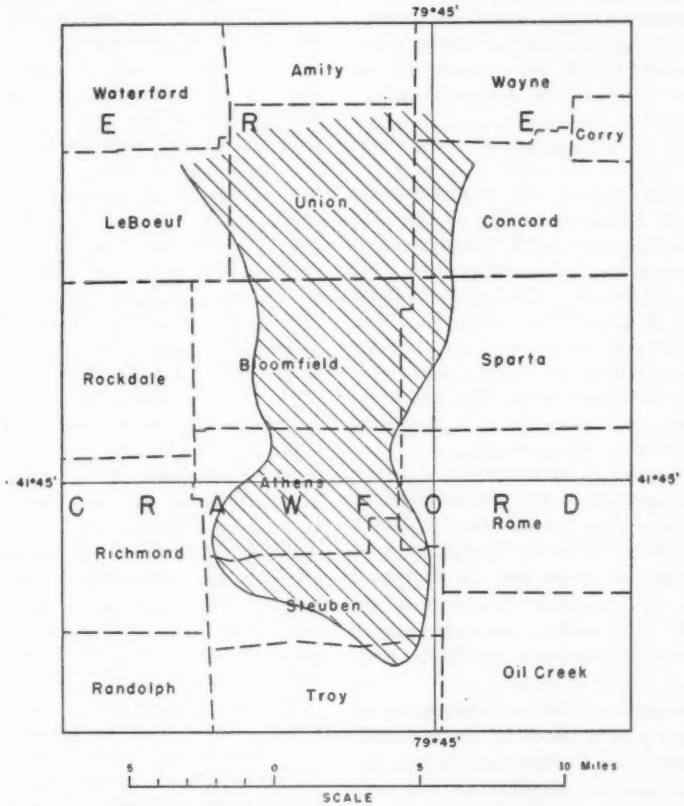

FIGURE 10.—AREA OF THE HUNGRY RUN SANDSTONE MEMBER OF THE ORANGEVILLE SHALE IN ERIE AND CRAWFORD COUNTIES, PENNSYLVANIA

The Hungry Run sandstone member is 12 feet thick at the type locality and 8 feet thick in an exposure 500 feet west of Pages Corners on the road to Canadohta Lake, Bloomfield Township. At this exposure, the upper foot of the sandstone is conglomeratic. Two feet of the massive Hungry Run sandstone member caps 6 feet of massive siltstone of the Corry on State Route 77, 1 mile west of Riceville, Pa., and about 5 feet of massive sandstone overlies the Corry in a small gully 500 feet south of the outcrop on the road.

Throughout much of the eastern part of its outcrop, the member rests on the Corry sandstone. The Bartholomew siltstone either was not deposited in this area or was removed by erosion. In the southwestern part of Athens Township, the Hungry Run overlies the Cussewago sandstone and both the Bartholomew siltstone member and the Shellhammer Hollow formation are absent. There the basal part of the Hungry Run sandstone member appears to contain some reworked sand of the Cussewago, which suggests that the Bartholomew siltstone

member and the Shellhammer Hollow formation were scoured away during the deposition of the basal part of the Hungry Run sandstone member.

The rocks above the Hungry Run sandstone are not exposed at its type locality. In southern Athens Township and northern Steuben Township, Crawford County, the sandstone is overlain sharply by dark silty Orangeville shale.

Correlation

Although an unconformity is present at the base of the Cleveland member of the Ohio shale in eastern Cuyahoga County, the Cleveland appears to grade into the upper beds of the Chagrin shale at many places, especially in the vicinity of the Grand River valley. The Cleveland member may be equivalent to some of the upper massive siltstones of the Chagrin shale in eastern Ashtabula County, Ohio, and to the upper part of the Riceville shale in western Crawford County, Pennsylvania.

The Cussewago sandstone is not a part of the Berea sandstone, as has been advocated by some geologists, but is a separate and distinct formation. Demarest's subsurface study in western Pennsylvania shows that the Cussewago sandstone is the surface equivalent of the Murrysville sand, which is generally assumed to be lower Mississippian in age (Weller *et al.*, 1948, Pl. 2, facing p. 188).

The assumption that the Cussewago sandstone was a part of the Berea sandstone gave rise to the concept that the Berea in Ohio is a three-fold formation composed of two sandstone members separated by a shale member. However, surface and subsurface studies show this concept to be incorrect.

The Bedford shale and the Berea sandstone comprise a cycle of deposition in much of Ohio, although the two formations are separated by an unconformity in the vicinity of their type localities. This unconformity is very marked in northern Ohio, but it is relatively local in extent and represents an exceedingly short time break. The Bedford shale extends to the east across northeastern Ohio and northwestern Pennsylvania to the vicinity of Meadville, where the shale loses its identity by grading laterally into the western part of the Shellhammer Hollow formation. In northwestern Pennsylvania, the Bedford shale includes the shale that was named Cussewago by White (1881, p. 94–95) and Hayfield by Chadwick (1923, p. 69). The writer's work leads him to believe that the beds called Cussewago shale or Hayfield shale are the Bedford shale. Because the name Bedford has priority, the names Cussewago shale and Hayfield shale are invalid.

In its sandstone facies, the Berea extends from its type locality eastward into the valley of the Grand River in western Ashtabula County and western Trumbull County, where the sandstone grades into siltstone. The siltstone facies of the Berea extends to the east to the vicinity of Meadville, where the Berea loses its identity by grading laterally into the western part of the Shellhammer Hollow formation.

The Corry sandstone extends westward from its type locality to the vicinity of Riceville, where it grades laterally into the eastern part of the Shellhammer Hollow formation. The Berea sandstone and the Corry sandstone, although separated laterally by the shales and intercalated siltstones of the Shellhammer Hollow formation, are probably equivalent in time, but the Corry sandstone is not an eastern facies of the Berea sandstone as has been suggested by some geologists (Prosser, 1912, p. 396; Caster, 1934, p. 122, 163–165).

The similar appearance of the Corry sandstone in eastern Crawford County to the siltstone facies of the Berea in western Crawford County led White to identify the siltstone facies of the Berea as Corry in western Crawford County. Thus the Corry sandstone was erroneously identified far west of the place where it feathers out, and correlations based on this misidentification gave the impression that the Corry was the eastern part of the Berea sandstone. When the eastern limit of the siltstone facies of the Berea and the western limit of the Corry sandstone were established, the relation of the Berea to the Corry became obvious.

Both the Corry sandstone and the Berea sandstone are lower Mississippian in age, and are equivalent to rocks in the Kinderhook series (Weller *et al.*, 1948, Pl. 2).

Geologic History

In late Devonian time, the mapped area lay below the shallow water of a broad epicontinental sea, and the shore line of the broad Catskill delta lay to the east and southeast. Black mud of the Cleveland member of the Ohio shale accumulated in the slightly deeper water in the western part of the area at the same time that the silt which now forms the upper part of the Chagrin and Riceville shales was deposited in the eastern part of the area.

The Cussewago delta fan was deposited in the southeastern part of the area in early Mississippian time. At first, the sand was deposited subaqueously, but, as sediment continued to accumulate, the surface of the delta projected above water at some places and mud cracks formed in some of the finer-grained Cussewago sediment. At about the time of maximum extent of the Cussewago delta, slight uplift occurred in southern Ontario, and sediments derived from the erosion of this upwarped area were carried southward and deposited as Bedford muds in the shallow sea that covered northern Ohio. Although deposition of sand had almost completely ceased on the Cussewago delta, currents were actively sorting and winnowing the upper part of the Cussewago at some places. Sand, silt, and mud were being deposited in the eastern part of Warren County, Pennsylvania. As deposition of the Bedford continued, the Euclid and Sagamore silts accumulated, probably as offshore bars like the Second Berea bar (Pepper *et al.*, 1944) of southern Ohio. A considerable amount of the silt in the Bedford appears to have been derived from the erosion of the upper beds of the Chagrin shale in an uplifted area north of Lake and Ashtabula counties, Ohio. Probably sometime near the close of deposition of the Bedford shale, the basal beds of the Corry sandstone were deposited in the western part of Warren County, Pennsylvania. Silt and mud of the Bedford spread eastward and overlapped the western part of the Cussewago delta; but the central part of the delta was a shoal area that acted as a barrier to eastward deposition of Bedford sediments excepting a small amount of silty mud deposited in the Shellhammer Hollow formation.

Renewed and more vigorous upwarp in Ontario and northern Ohio brought about a short period of stream scour, during which channels were cut deeply into or through the Bedford rocks in much of northern Ohio. Deposition of Corry sediment continued, and the fan of silty sediments lapped up on the eastern side of the Cussewago delta. The sediment did not cross the barrier of the Cussewago delta, which formed an extensive shoal area in central Crawford County and southcentral Erie County.

Subsidence followed the channel cutting in northern Ohio, and the scour channels were soon filled with large amounts of sand that were carried into the area by the streams in early Berea time. The rapid filling of the scour channels produced the channel sandstone phase of the Berea in northern Ohio. For a time the amount of subsidence did not depress the land area in northern Ohio below the epicontinental sea, and the sand of the Berea accumulated in a large delta, the eastern part of which covered much of Cuyahoga, Geauga, and Lake counties. The subaerially deposited sandstone that makes up the fluviatile phase of the Berea is characterized by much steep-angle cross-bedding. Silt was the dominant type of sediment being deposited east of the delta area. During the rest of Berea time, a transgressing sea from the south moved the shorelines of the delta northward and spread a thin sheet of marine sand over the delta surface. Deposition of silt continued to the east, and the silt facies of the Berea spread into northwestern Pennsylvania, where its eastern extension was halted by the shoal area over the slowly settling Cussewago delta. As in Bedford time, only a thin wedge of sediment was deposited on the highest part of the Cussewago delta, and this sediment is included in the present writer's Shellhammer Hollow formation.

The Corry sandstone probably reached its maximum spread at about the same time, and the westernmost silts of the Corry were similarly incorporated in the sediment that makes up the Shellhammer Hollow formation.

Black mud was deposited over the area at the close of Berea time. Silt deposition recurred locally in northern Ohio, when the Aurora and the Chardon members accumulated. One short

but widespread period of silt deposition occurred in northwestern Pennsylvania, when the Bartholomew siltstone member of the Orangeville shale was deposited.

At about this time the small delta of the Hungry Run sandstone member of the Orangeville shale was deposited in the eastern part of Erie County. The delta was built southward into the shoal area that was formed by the eastern part of the Cussewago sand body. Possibly the absence of the Shellhammer Hollow formation and the Bartholomew siltstone member of the Orangeville shale in sections in Athens, Richmond, and Steuben Townships, Crawford County, may be the result of scour by the currents that swept the coarse sand of the Hungry Run into this area.

The deposition of mud continued for some time in northeastern Ohio, and a considerable thickness of Orangeville sediment accumulated. In northwestern Pennsylvania, however, silts and sands were being deposited in eastern Crawford County and western Venango County soon after the close of Corry deposition. This deposition of silt and sand continued and spread farther to the west, displacing the muddy sediment before it. At some places, the western advance of the silt and sand was halted temporarily, and a massive clean silt body accumulated. The western encroachment of silt and sand continued and the Sharpsville sandstone spread across the mapped area.

Conclusions

The present writer traced the Bedford shale and the Berea sandstone eastward into the vicinity of Meadville, where they grade laterally into a thin unit that is here named the Shellhammer Hollow formation. The Cussewago sandstone, which is an excellent unit for tracing over much of northeastern Ohio and northwestern Pennsylvania, is not a part of the Berea sandstone as was thought by some geologists, but is a separate formation. The Cussewago sandstone was deposited as a large delta in western Pennsylvania, and a part of this delta formed a shoal area in the northwestern part of the State that stopped the eastern spread of Bedford and Berea sediments. The writer also traced the Corry sandstone westward from its type locality into the Shellhammer Hollow formation in the vicinity of Riceville, thus showing that the Berea sandstone and the Corry sandstone are close time equivalents, even though the Corry sandstone cannot be considered a facies of Berea deposition. In working out the stratigraphy of the Berea sandstone in northwestern Pennsylvania, the writer mapped a geographically extensive siltstone characterized by many short curved markings—the Bartholomew siltstone member of the Orangeville shale. Tracing the Cussewago sandstone and the Bartholomew siltstone member of the Orangeville shale carefully throughout northeastern Ohio and northwestern Pennsylvania is the key to working out the stratigraphy of the lower Mississippian rocks in that area.

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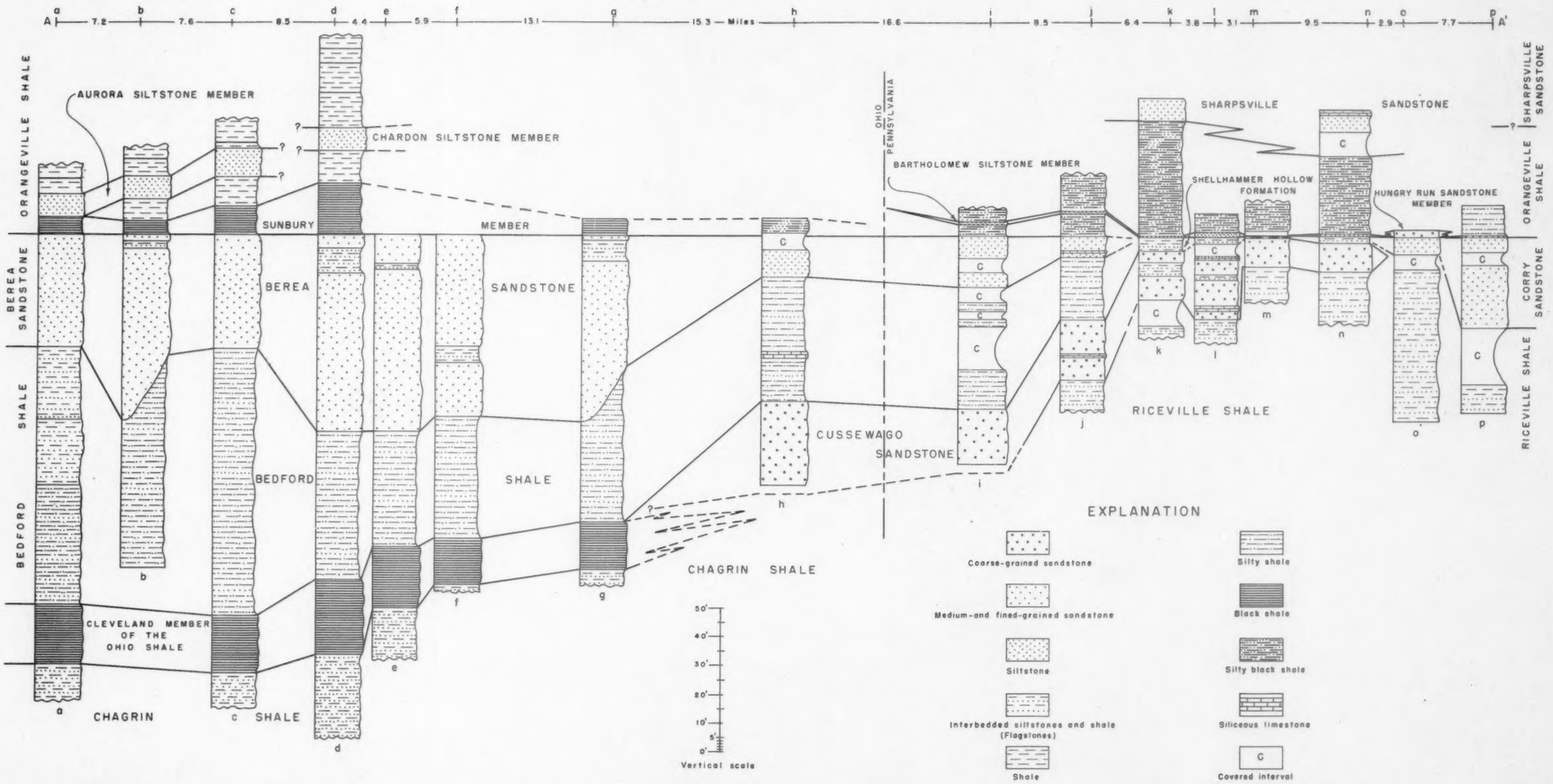

STRATIGRAPHIC SECTIONS BETWEEN BEDFORD TOWNSHIP, CUYAHOGA COUNTY, OHIO, AND SPARTA TOWNSHIP, CRAWFORD COUNTY, PENNSYLVANIA, ALONG LINE A—A' SHOWN ON PLATE 1

Sections a-g adapted from Prosser (1912).

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Short Notes

BLUE RIDGE FRONT—A FAULT SCARP

By G. W. Stose and Anna J. Stose

White (1950) interprets the hard-rock geology of the Appalachians largely from a study of the topography and concludes that the presence of a normal fault at the foot of the scarp is the plausible explanation of the Blue Ridge Front. He postulates that a Triassic basin formerly paralleled the scarp on the east, with a western border fault that was reactivated, probably during the late Tertiary, to create the present Blue Ridge scarp. He regards the trellis drainage in an extensive area of lower relief along the foot of the scarp as an indication of former Triassic basins from which the sediments have been wholly eroded, and refers specifically to the "Morganton and Wilkesboro basins" in North Carolina as examples of such stripped Triassic basins and to the Blue Ridge front to the west as the uplifted northwest side of this basin. The straight base line of South Mountains and Brushy Mountains, which face the Blue Ridge, he interprets as the expression of a border fault on the eastern side of the "Morganton and Wilkesboro Triassic basins." These topographic basins are underlain by gneisses and schists and contain neither Triassic sediments nor diabase dikes or flows, which occur in and near all known Triassic areas of the Appalachians. There are no observable normal faults bounding these basins at the foot of the Blue Ridge scarp, so that White's theory that they represent faulted Triassic basins is subject to serious doubt.

White bases his evidence of normal faulting largely on the presence of manganese-coated, slickensided surfaces in the gneisses at the foot of the scarp, and states that most of the surfaces have probably been displaced only a few inches or fractions of an inch, but collectively they may indicate significant faulting. He plotted this information in a form that simulates diagrams of rock-fabric analyses, on the "lower hemisphere of the stereographic net, using the poles of the surfaces and the actual points of emergence of the striations." He states that the surfaces of these planes are usually inclined steeply to the southeast, and the direction of movement "shown by the points of emergence of the striations" persistently tends to parallel the dip of the surface. The question is—Was the movement on these surfaces in the appropriate direction? The area shown in White's Figure 1 is in North Carolina northeast of Marion and includes a region that we have studied in detail for a paper on the Grandfather Mountain window (Stose and Stose, 1949). The window is framed by the Fries overthrust block and is overridden on its south side by the Brevard thrust, which is a later fault than the Fries overthrust. The Brevard thrust from Old Fort northeastward roughly parallels the "Blue Ridge border fault," so-called by White in his Figure 1, to the point west of Wilkesboro where he offsets this fault to the northwest. There the Brevard thrust leaves the front of the Blue Ridge and follows the Yadkin River to Wilkesboro, northeast of which we have not traced it. The Brevard thrust does not stop at Old Fort, the southwest end of White's inferred Triassic Basin, but continues as a less-pronounced scarp southwestward across the Blue Ridge front. We have traced the Brevard thrust south of North Carolina to the Coastal Plain border in Alabama. The thrust throughout this region is straight, strikes in general about S. 45° W., and dips 45° to 60° SE. Although it truncates other Appalachian structures, it also was formed in that orogeny. Along the thrust, the granite gneisses are mylonitized in a band half a mile or more wide. A mylonite is a microscopic pressure breccia with fluction structure, showing that the rock was crushed under conditions of compression where it could not lose coherence. The mylonites include augen schist and dense even-grained, flinty crush rock. We have observed mylonite characteristic of the Brevard

thrust at many places where White has shown a normal fault, namely near Old Fort, Joy, Adako, Collettsville, and Patterson. This fault is the result of compression and not of tension, and the movement is to the northwest, which is the reverse of the movement postulated by White on his "Blue Ridge boundary fault." We have found no evidence of deformation later than the formation of the mylonite, and conclude that the Brevard thrust is the latest fault movement in the area.

When White presented this paper (White, 1946) at the meeting of The Geological Society of America at Chicago, we called his attention to the mylonitized belt along the Brevard thrust, which at that time he had not recognized. In his paper he mentions the southeast-dipping schistose planes along the Brevard thrust but regards their dip of 40° to 60° as too steep for Appalachian structures. With this conclusion we cannot agree, for throughout the crystalline belt of the southern Appalachians we have mapped many thrusts of Appalachian age with similar dip. Known normal faults of Triassic age are all nearly vertical, hence much steeper. They are accompanied usually by brecciation and fault gouge, indicating a lack of compression, and never by mylonitization.

In Maryland, where Stose (1927) first postulated a late post-Cretaceous movement to account for the uplifted Tertiary Schooley surface, there are known normal Triassic faults on the west side of the Triassic area. During physiographic studies in Virginia and North Carolina a similar explanation was sought for the Blue Ridge front. The Triassic sediments, which extend from Maryland southwestward into Virginia, diverge increasingly from the Blue Ridge front from Leesburg southwestward, and near Orange they end in normally down-dropped blocks. Other Triassic basins lie in the Piedmont still farther east. The suggested explanation that the Blue Ridge scarp in Maryland is the result of a post-Cretaceous normal fault does not seem to apply in Virginia. We have mapped the crystalline rocks of the Blue Ridge uplift of Virginia, where White has suggested the presence of reactivated Triassic faults, but have found no evidence of such normal faults. The faults in the area, like the Brevard, are all southeast-dipping thrusts, marked by mylonite and on which the movement was to the northwest.

White does not mention that the Schooley peneplane in North Carolina is not clearly marked because the surface was not worn down to the peneplane level at the time it was formed, and his Figure 1 pictures the unreduced upland surface. At Blowing Rock and vicinity the Schooley peneplane stands at 3400–3600 feet altitude, and throughout the Blue Ridge plateau in North Carolina the surrounding mountains rise to over 4,000 or 5,000 feet altitude, culminating in Mt. Mitchell, 6684 feet. We favor the explanation of William Morris Davis (1904) for the two levels of the Schooley peneplane in the Southern Appalachians—that stream systems of different lengths, working simultaneously to the same base level, would produce the present results without a fault. All the streams from the crest of the Blue Ridge westward are part of the Mississippi drainage. The Atlantic drainage east of the crest is much shorter and more active, hence has reduced the Schooley peneplane to a much lower level. The merging of the two peneplane levels is illustrated on the north side of the Blue Ridge Plateau, southwest of Salem, Virginia, where North and South Forks of Roanoke River of the Atlantic drainage have attacked the higher level of the Plateau and reduced it to lower levels.

White's article is based largely on an attempt to find evidence of normal faulting in the "Morganton basin," southeast of the Blue Ridge scarp. For some distance in this region the trace of the Brevard thrust roughly coincides with the scarp, and White interprets the evidence of faulting there as favoring his theory. The thrust, marked by mylonite, was formed in the Appalachian orogeny, and the movement was to the northwest. There is no indication of movement later than the mylonitization on the thrust. Therefore White's detailed study of the structural features, insofar as they are related to the Brevard thrust, have no application to the cause of the Blue Ridge scarp.

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